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Experimental Analysis of the Sensori-Motor Consequences of Passive Oscillation, Rotary and Rectilinear

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I. INTRODUCTION

When one is rotated about a fixed axis, the amount of rotary motion may be expressed in terms of angular change, but the actual translation of any part of the body through space will be determined by the distance of that part from the axis of rotation. If one is moved in straight lines as in an elevator, the angular change is zero, while the entire translation through space is rectilinear. On the contrary, if one sat over the axis of rotation of a revolving chair, the rectilinear component for any part of the body would be small even when the angular velocity became so great as to injure the organism.

Both rectilinear and rotary components are involved in most passive motion of an organism, and it might be expected that each would differentially affect some receptor mechanism or mechanisms if the organism is to make adequate compensation or other adjustments to maintain its equilibrium. The specific receptor organs for the rotary component of passive motion are traditionally believed to be the semicircular canals. We know something of their sensitivity, the consequences of repeated and protracted rotation, and the reflexes which they originate. What receptor organs are affected by the rectilinear component is not so clear. We know nothing of their sensitivity, nothing of the consequence of repeated and protracted stimulation, and relatively little of the reactions which they evoke.

In the present paper we shall present data bearing on the relative sensitivity of the receptors for the two components of passive movement, their interplay under certain conditions, as well as the importance of extra-vestibular, kinaesthetic factors and the reflexes which they evoke. The effects of repeated and protracted stimulation of the receptor apparatus for rotary and rectilinear oscillation have not yet been explored; neither has sine-wave intermittent rotation, with duration independent of frequency. Both these questions are now under investigation. In an unusual

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degree, however, our experiments permitted us to follow some of the complications of response and relate them to definite phases of the receptive and elaborative processes. We believe they give us new insight into the complication of the conditions of response and promise new light on the conditions of human variability. This, at least, was the hope which underlay the investigation.

It seemed that the precision with which the movement stimuli could be applied and measured, together with the relative simplicity of the receptor mechanisms and the reliability of the reaction indicators, made almost ideal conditions, not only for a study of receptor sensitivity, the complication of sensory data and the integration of response, but also for the effects of stimuli on either side of the limen, the phenomena of adaptation, the incidence and effects of central factors, the negative effect of faint stimuli, and functional periodicity.

In order to provide a protracted succession of stimulations of the receptor fields for passive movement, we selected sine-wave oscillation. This selection had a certain theoretical as well as practical justification. The several labyrinthine receptors, *i.e.*, the cochlea, the semicircular canals, and possibly the utricle and saccule may be looked upon as peculiarly adapted for the sensing of oscillation frequencies ranging from one oscillation in one or more seconds in the case of the canals to many thousand vibrations per second, in case of the cochlea. Where the function of one specific sense organ of this group ends and that of another begins is difficult to determine. Practically, sine-wave acceleration such as sine-wave oscillation provides is one of the best means of obviating the jars at the beginning and end of movement, and involves a relatively simple driving system.

The psycho-physiological tradition is not altogether clear as to the division of function in the several vestibular organs. It is definitely established that the semicircular canals function in the perception of angular changes of the head, the adequate stimulus being some change in the rate of rotation. Whether the canals also function in the perception of rectilinear changes or whether some other vestibular organ (saccule or utricle) acts as the receptor for rectilinear motion seems to be still a question. In

lower animals (frog) the saccule apparently has nothing to do with maintaining bodily equilibrium and the utricle functions in static relations of bodily posture. If the same holds true in case of man, we must question whether the canals also function in the perception of rectilinear motion.

Due to the fact that the stimulus for the arousal of vestibular sensory data is purely mechanical, it is rather easily and simply applied and controlled; but the results in consciousness and the overt responses resulting from vestibular stimulation are not so simply observed. In the preliminary exploration of vestibular data trained observers seemed highly desirable. Consequently, we have endeavored to go as far as possible with two observers in the observation of fundamental aspects of the phenomena relevant to vestibular excitation by oscillation.

Voluntary, manual, compensatory movement of the arm and hand in the case of rotary oscillation, and of the fingers in the case of rectilinear oscillation, was employed as the means of response to the perception of oscillatory motion. This compensatory movement was recorded mechanically on the smoked drum of a kymograph through a specially devised lever system, which was modified for the various bodily positions. Accompanying introspections were recorded as an experimental check of the graphic records. This method of response gives a fairly accurate representation of the direction, speed, and extent of the perceived motion.

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II. HISTORICAL ORIENTATION

Griffith's (1) exhaustive survey of the literature on vestibular equilibration includes references to the literature on biological, physiological, anatomical, clinical, and psychological aspects of the problem from 1575 to 1921. We quote directly from his summary and conclusions.

"(a) Only a part of the inner ear is concerned solely with hearing. The remainder,—*viz.,* the semicircular canals and the utriculus and sacculus,—seems to be very closely connected with the maintenance of bodily equilibrium. (b) The structure of the end-organs in the ampullae and in the vestibular enlargements is such as strongly to suggest such a function. Furthermore, differences in the structural complexity of these end-organs among the vertebrates and corresponding differences in equilibratory ability are striking. (c) The theory that actual movements occur in the liquid in the canals or in the ampullae has little in its favor but small changes of pressure may occur in the system in such a way as to excite the delicate endings of the vestibular branch of the VIIIth nerve. Conclusive evidence regarding the mode of operation of the end-organ has apparently not been secured. (d) There is evidence that the excitation of the equilibratory end-organs affects the ability of an organism to maintain its position. By means of these organs the body becomes sensitive to changes **in either translational or rotational* movements. Frequently the organism makes a variety of compensatory movements to such displacements of its position. (e) Histology has demonstrated that the cerebellum is, in a sense, a suprasegmental development of the vestibular nucleus of the VIIIth nerve, a fact which strengthens the belief that the end-organs in the canals are closely related to motor control. Other central connections are, however, but imperfectly understood. (f) The apparent demonstration that the canals are phylogenetically related to the lateral line canals and that the latter are probably equilibratory organs gives a genetic warrant for the assumption that the canals bear a similar function. (g) A great deal of pathological evidence from the clinical laboratory testifies still more directly to the equilibratory functions of the end-organs in the canals or in the vestibular enlargements.

In brief, the location of the canals, ... their general form and structure, their relation to the lateral line canals, their central connections, their mode of excitation, the results of pathological . . . . . **changes and operative experiments all indicate that they function in maintaining the equilibrium of the body. The facts do not show, however, that they are the sole organs. On the contrary there is evidence that they are regularly supplemented by other receptor organs, even in the perception of rotation.*"

* Italics ours.

In connection with the differential operation of the several receptor organs of the labyrinth Wilson (2) has briefly summarized the extensive work of Magnus and Kleijn in a recent article. They distinguish between the functions of the semicircular canals and the functions of the otolith organs. The canals were found to function as receptors for rotation, the otolith organs for position and, probably, rectilinear movement.

By experiments on dogfish Maxwell (3) has shown that both the otolithic organs (utricle) and the ampullae (semicircular canals) function in both static and dynamic equilibration, and that the saccule has nothing to do with maintaining bodily equilibrium, thus confirming the work of Parker (4).

McNally and Tait (5) found that the semicircular canals in the frog function in dynamic equilibrium and the utricle in static equilibrium. This seems to conflict with Maxwell's report. He found that (1) posture reflexes for oblique positions in all planes can be mediated by the otolith organ of the utriculus alone and (2) that the semicircular canals have definite static functions. It is possible that the divergence of results between Maxwell's experiments on dogfish and McNally and Tait's experiments on the frog is due to the difference in the phylogenetic levels of the animals involved. Pike (6) made a recent critical survey of the literature on the function of the vestibular apparatus at the various phylogenetic levels. In the light of this work we should at least be cautious in applying results obtained on any of the lower animals to the interpretation of human behavior.

Some of the more recent psychological attempts at analyzing vestibular functions have centered upon the bodily adjustments and motor aspects of the problem. Miles (7) and Fearing (8) investigated the factors which influence static equilibrium in determining variations in body sway under different conditions, Dunlap (9), Holsopple (10), Griffith (11), and Dodge (12) centered their attention on nystagmus as indicative of vestibular stimulation.

The experiments by Dodge on habituation to rotation and rotation thresholds constitute a direct introduction to the present approach to the problem. In his first paper on one human subject,

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Dodge showed that post-rotation nystagmus decreases from record to record within each experimental day and from day to day throughout the experiment for both slow and quick phases of the eye movements. The quick phase becomes habituated first, thus confirming the traditional assumption that the two phases have different central origins. In an effort to measure the sensitivity of the canals, Dodge found a rotary threshold at angular velocities between 1 and 2 degrees per second, with various modes of onset, but he also found that judgments of direction were often false at double these velocities. With rotary *oscillation* as the stimulus, the same author found that the saccadic or quick-phase movements of the eyes disappear first, and then the slow movements. The results correspond with those obtained on protracted rotation. These are the only experiments with which we are acquainted in which oscillation was employed as the stimulus.

As far as we know, controlled human experiments on the perception of rectilinear translation have never been made with respect either to its origin or its threshold. Systematic comparison of the amplitude, frequency, and duration of oscillation have not previously been attempted in either rectilinear or rotary motion.

III. METHODS AND TECHNIQUE

A. General Statement

It is assumed that the adequate stimulus for the excitation of the semicircular canals is the appropriate angular movement of the head, and that rotation of the head in any plane will differentially stimulate one or more of the canals. Since the relative positions of the canals are known, conditions can be established whereby one canal system will be principally excited with a minimum excitation of the others. Largely in the interests of simple techniques the canal receptors for motion in the horizontal plane were selected for experimentation. The subject sat in an upright position with the head held in an approximately fixed position by head rests, so that rotation of the body and head in a horizontal plane stimulated predominantly the horizontal canals. It is assumed that any change in angular motion in the horizontal plane, whether starting from zero or a certain velocity, stimulated the appropriate canal.

The main technical requirements included a rotating chair that could be oscillated smoothly at or near threshold speeds for a variety of known amplitudes and angular velocities, a suitable reacting system by which the subject could indicate the direction and extent of apparent motion, and a recording system which would show both actual and apparent motion.

The experimental situation with respect to rectilinear oscillation was less clear. Whether the canals function at all in rectilinear translation, whether opposed canals are equally stimulated and balance out, or whether the perception of rectilinear motion depends on receptors exclusive of the canals was unknown and constituted one of the questions at issue. We consequently varied our procedure to emphasize different receptor organs in succession. The main technical desiderata did not differ essentially in the two cases, but the devices were modified to fit the changed

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situation. The main difference was the substitution of a smoothly rolling for a rotating chair.

While our technique did not entirely separate the relative rôles which the several receptors of the vestibule play in the perception of rectilinear motion, supposititiously, the differential excitation of the canals is reduced to a minimum in straight line acceleration. The supposed mechanics of the canals are such as to justify the hypothesis that some other organ has the dominant rôle. The relative rôles of other senses—vision, audition, the cutaneous and kinaesthetic senses—were studied by varying the conditions of the experiment in both rotary and rectilinear oscillation.

Preliminary experiments in passive rotary oscillation of the body indicated that when the axis of rotation runs between the canals the oscillation seems to be pure rotation. When one canal is farther from the axis than the other, the perception of oscillation may be simple rotation, motion on an arc, or pure rectilinear motion, depending on the amplitude and period of oscillation and the distance of the body from the axis.

We controlled the two physical factors of harmonic motion—namely, the amplitude and frequency of oscillation. These determined the frequency and intensity of the stimuli. Both could be accurately recorded by suitable lever systems and compared with the records of compensation.

B. The Instrumental Arrangement for Rotary Oscillation with the Subject at the Axis

The apparatus for rotary oscillation consisted of an approximately frictionless rotating platform, a driving mechanism, and a recording system as illustrated in figures 1 and 2. The rotating platform was the same as that used by Dodge in his various studies of rotation. The driving mechanism consisted of a practically noiseless Pathé spring motor, large size. A cone of pulleys, P1, attached to the main spindle of the motor was connected by belt to a cone of reducing pulleys, P2, which in turn were connected by belt to a crank pulley, P3. Thus driven, the crank pulley, P3, rotated at a uniform speed and oscillated the platform

by means of a driving rod. The harmonic motion produced by the driving rod approximated the accelerations and decelerations of a series of sinusoidal waves. That is, at each thrust of the driving rod the platform was accelerated until the driving rod reached the middle of its stroke. This was followed by a period of deceleration which lasted until the end of the thrust. At the end of the thrust the direction of positive and negative accelera-

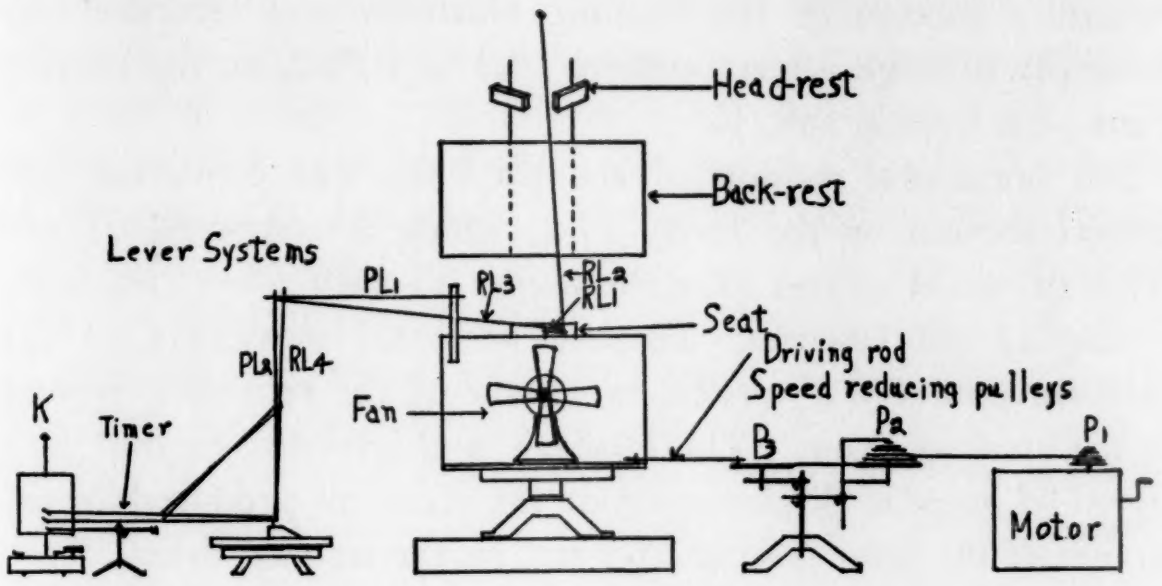

Fig 1. Elevation of Recording System, Rotating Platform, and Driving Mechanism

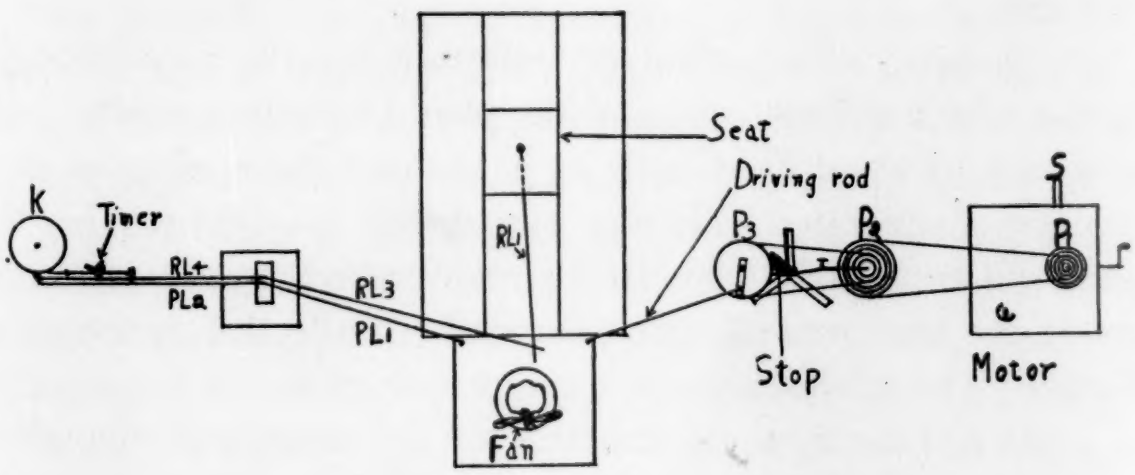

Fig 2. Plan of Recording System, Rotating Platform, and Driving Mechanism

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tion was reversed as the driving rod pulled the platform toward the pulleys.

The speed of oscillation could be varied from one complete oscillation in 120 seconds to one oscillation in one-half second by various combinations of pulleys, P1 and P2, and suitable adjustment of the motor regulator. The crank pulley, P3, was equipped with an adjustable sliding sleeve which permitted a range of displacements from 0 to 12 degrees in amplitude. The oscillatory motion of the rotating platform was recorded mechanically through a lever system, PL1 and PL2, on the smoked drum of a kymograph, K.

The horizontal motion of the platform was converted into vertical motion by the lever, PL2, which is composed of two strips of wood joined at right angles to each other, the apex serving as the fulcrum. Thus, a horizonal movement of the platform produced a vertical excursion of the recording pointer on the smoked drum. The leverage was adjusted so that each degree of angular displacement of the platform produced an excursion of the lever pointer of 1 cm. on the smoked drum. Each cm. of adjustment at the crank pulley, P3, in turn equaled 1 degree of angular displacement of the platform. This arrangement was rather convenient because the curves always gave exact data concerning the speed and extent of movement of the platform.

The problem of an adequate indicator for the perception of motion was a difficult one, and the plan adopted—namely, holding a strip of wood fixed in space, gave much more adequate data than verbal response. This type of response involved moving the hands and arms in the opposite direction from the apparent direction of the platform the same angular distance and at the same velocity. The advisability of a compensatory motor response of the arms and hands as an indicator of the perception of motion may be questioned, but it is the best method we could devise to give a consistent record of the extent, speed and frequency of the perceived oscillations. It proved to be a natural and easily habituated response, which even at first required very little of the subject's attention. The recording of compensatory arm and hand

movements on the same scale as the records of the moving platform might be accomplished in a variety of ways. Several lever devices were tried out, of which the following had the least apparent sources of error and was finally adopted.

In order to preserve the same leverage in the recording system independent of the exact position of the hands, the reaction arm on which the hands rested was the hypotenuse (RL2, Fig. 1) of a right triangle whose long side was oriented as a vertical axis coincident with the axis of the chair and whose horizontal side (RL1, Fig. 2) was adjusted to give the appropriate leverage of the reaction system. The horizontal arm (RL1 in Fig. 2) was a thin wooden strip, pivoted at one end at the axis of rotation of the platform, just under the subject's seat. The other end made a frictionless joint with RL3, which, in turn, articulated with the recording lever (RL4). In order to make the curves of reaction comparable with the records of the platform, two conditions must be fulfilled: (1) the distance from the axis of rotation to the articulation of RL1 and RL3 must equal the distance from the axis to the articulation of the platform and its recording lever, PL1; (2) the recording levers (RL4 and PL2) must be identical in construction. Since the compensatory lever triangle was oriented about the axis of the rotating platform, if the reactor's hands were actually held still in space they might rest anywhere on the hypotenuse without altering the record.

Two general principles of construction characterized all our levers. They are as follows: (1) The recording arms were long enough to prevent gross distortion of the records on the curved surface of the drum. That is, they should write in lines which are approximately straight when the kymograph is at rest. Our recording arms were 75 cm. long. (2) All axes of rotation were as free as practicable from friction, backlash, and slip. All our lever axes were made of notched thin tin plate, making virtually knife edge bearings.

The platform recording system gave a sinusoidal curve, and the deviations of the response curves from the platform curves showed the errors of compensation which could be read directly from the records in terms of time and angular extent of movement. A special transparent celluloid scale facilitated reading.

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C. Instrumental Arrangement for Rectilinear Oscillation

A side view of the scheme of the rectilinear platform, including the driving mechanism, the relations of the rectilinear to the rotary platform, and part of the lever systems is shown in Fig. 3. (See Fig. 1 for the recording levers.) The platform, 80 cm. square, was supported horizontally on two rolling brass segments which are joined by a cross bar and roll on two flat plates of brass mounted on tripod bases with leveling screws. The platform rests on two knife-edges at the geometrical centers of the segments, which are 30 cm. in height. They are equivalent to two segments of a solid brass wheel the arc of which subtends an angle of 60 degrees. The knife-edge joints permit platform movement of about 10 cm., a distance greater than any used in our experiments. The platform was stabilized by a triangular support attached to the rotation platform. This support was hinged to both platforms, attaching to the rotating platform half way between the axis of rotation and the driving rod. Thus, to obtain one cm. excursion of the rectilinear platform, the driving rod must move two cm. The Pathé motor driving-rod mechanism drove the rotating platform, which in turn drove the rectilinear platform through the hinged support. Under service conditions with the rolling mechanism free from dust the resulting motion is remarkably smooth and free from noise, jar, or vibration.

A chair for the subject was mounted on the platform (indicated in dotted lines, Fig. 3) and held firmly by an upright to which it was screwed. An adjustable headrest (also in dotted lines) was clamped to the upright at an appropriate height above the back of the chair.

The recording lever systems of the rectilinear platform are similar to those of the rotation platform except for slight adaptations to the new conditions. The platform lever was practically identical to that in rotary oscillation. The response lever had an extension from RL4 in Fig. 1 through a friction slot at the side of the chair to a position where it could be easily grasped by the subject. When the subject was in position with his thumbs held

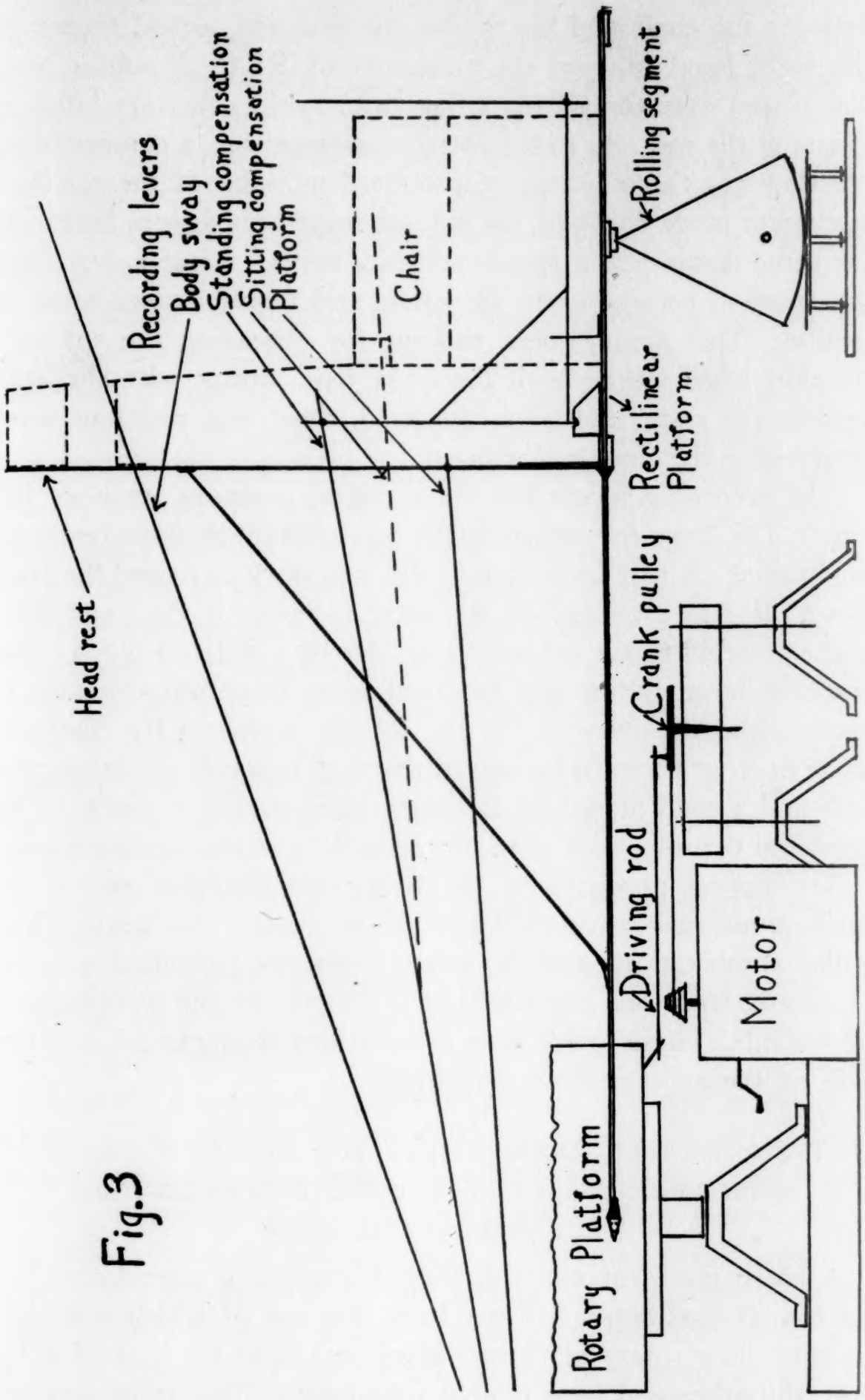

Fig.3

FIGURE 3. Elevation of the rectilinear platform, driving mechanism, attachments to rotary platform, and part of recording lever systems.

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between the chair and his thighs, the first and second fingers of the right hand grasped the extension of RL4. A rubber band was placed over the subject's fingers to avoid voluntary effort in grasping the rod. As in the rotation experiments, a compensating reaction was the indicator of perceived motion. If the platform seemed to move forward, the subject moved his fingers backward the same distance and speed; and *vice versa.* After a few trials the reaction became quite automatic and required very little attention. This arrangement sufficed for observing the subject's reaction when sitting with the body free, sitting with the head against the rests, and when the head, chest, and abdomen were strapped to the chair and support.

The recording levers for the standing positions were as follows: The lever for recording the platform movements remained unchanged. A new lever system was necessary to record the body sway. It was mounted on the same block with PL2 and RL4 and connected to the subject's shoulder by a strip of wood. The response lever system was modified so as to permit the body to sway without moving it. If the subject perceived the platform to be moving forward he moved the strip upwards by flexing the first and second fingers of the right hand, and *vice versa.* This produced the same sort of record as in the previous arrangements.

The curves produced by the rectilinear platform are of the same sinusoidal wave character as in rotary oscillation. The pulley combinations and the motor regulator permitted a range of speeds from one oscillation in 2 seconds to one oscillation in 32 seconds. These speeds were selected empirically to lie on either side of the supposititious threshold.

D. Instrumental Arrangement for Rotary Oscillation with the Subject at Varying Distances from the Axis of Rotation

A boom platform was constructed, consisting essentially of a flat top channel-beam, 340 cm. long, one end of which was supported by the rotary platform, which served as the axis of rotation, the other end by a double wire cable. This cable was led through an eye at the top of the rotating chair tripod-support

directly in the axis of rotation and anchored to the brick wall, thus eliminating most of the side thrust strain on the bearings of the rotation platform and providing rigidity. Turnbuckles at the point of attachment between cables and boom provided for leveling the latter. This instrument afforded a very smooth, noiseless oscillation of the subject, whatever his position along the boom platform.

The driving mechanism described in the previous sections was permanently attached to the distal end of the boom, 326 cm. from the axis of rotation. The same amplitudes and frequencies of oscillation of the boom were used for all four distances of the subject from the axis. By seating the subject at various positions along the boom in a specially constructed chair with foot-supports, back, and head rests, the rectilinear and rotary factors in oscillation could be experimentally combined in various proportions.

Lever systems gave objective records on a kymograph of the movements of the boom platform and the subject's manual compensation for both the rotary and rectilinear components. They were mounted on the platform, together with the kymograph, and operated analogously for all four distances of the canals from the axis—namely, 326 cm., 217 cm., 109 cm., and 3 cm., respectively. The levers, in most part, were attached to the subject's chair and were movable with the chair as the subject's position was varied.

A rigid support extraneous from the platform activated the platform lever on a fulcrum which moved with the chair when the platform oscillated. Two response levers, one for the rotary component, the other for the rectilinear, operated similarly to those in our previous experiments. Our main difficulty in constructing the response lever system was to obtain a mechanical relationship of the levers to the subject so as to give a reliable objective record of simultaneous or alternate compensation for the rotary and rectilinear components. We approximated this ideal in the following manner. An *L* lever was constructed with arms respectively 15 and 25 cm. A handle was attached to the apex of the *L,* another handle to the end of the longer side. At right angles to the end of the longer arm was attached the record-

ing lever for the rectilinear component; to the end of the short side was attached the recording lever for the rotary component. The subject grasped one handle in each hand. If he perceived the oscillation to be rectilinear, he compensated by moving both hands forward or backward in a direction opposite to the perceived motion. If the motion seemed to be pure rotary he moved both hands to the left or right; if he perceived the oscillation as describing an arc, thus moving one side of the body farther than the other, he compensated by moving the hand of the side of the greatest movement farther than the other, opposite to the direction of perceived motion. When the subject compensated by moving both his hands backward and forward in a straight line, only the lever for recording rectilinear motion was activated. Conversely, in the two hand compensation to the right and left only the lever indicating rotary motion was brought into action. When one hand was moved farther backward and forward than the other, in compensation for perception of motion on an arc, the levers for both components were brought into action differentially, indicating the curvature of the arc.

E. Experimental Procedure

In the experimental investigation of the relative importance of various receptors a particular set of precautions and controls are necessary for each sensory field, in order that its function may be accurately observed aside from the function of the others.

Vision is easily eliminated by properly covering the eyes. This covering, however, does not prevent reflex compensatory movements of the eyes to vestibular stimulation. The secondary cues obtained from the reflex movements of the eyes may aid the subject in the perception of motion and its direction, especially at the beginning of the stimulation period. It has been shown in a previous investigation (13) on habituation to rotation that the compensatory eye movements gradually die out in continuous vestibular stimulation, also that the reflex becomes gradually eliminated in repeated stimulation extending over several days. In the light of this investigation and our data, we assumed that

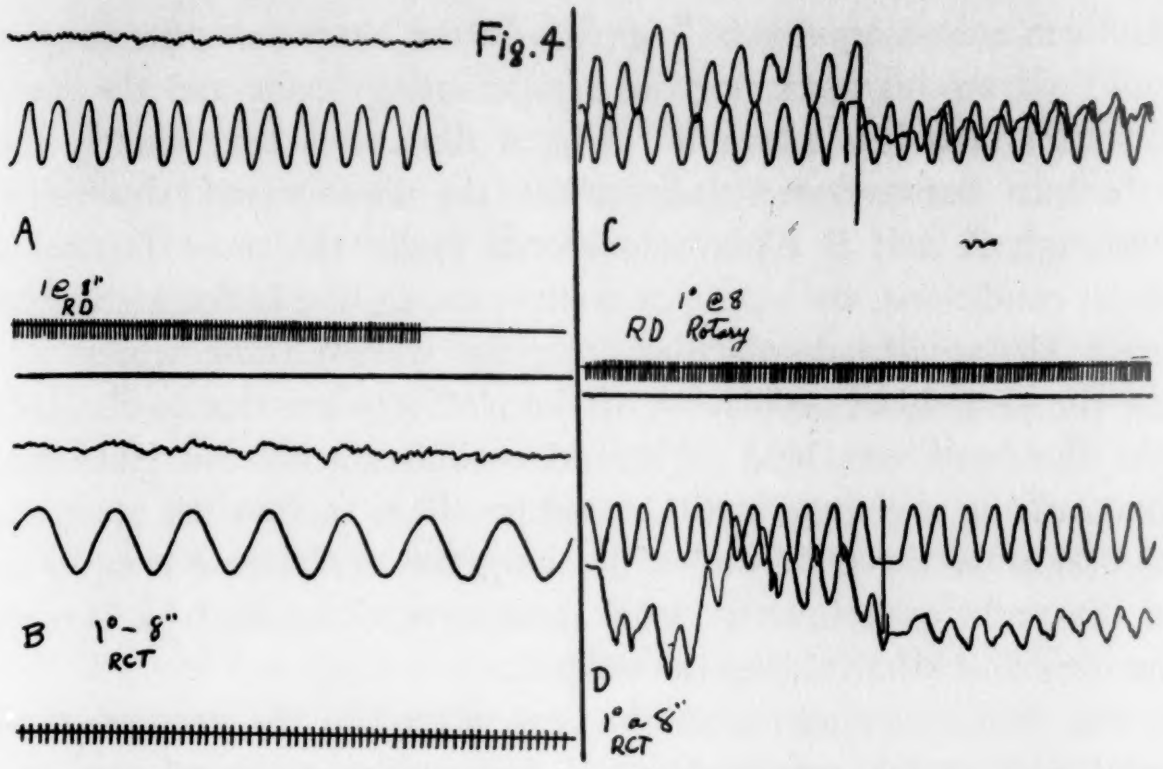

FIGURE 4.* Records of platform movement and manual compensation with and without visual cues. A and B are records taken when the subject sighted past the compensating lever to the floor. C and D are records taken without visual cues and with visual cues where the subject looked through a hole in a mask with the right eye focused on a radiator. A pointer moved with the platform across his line of regard.

the kinaesthetic cues arising from eye movements probably play a minor part in the perception of motion. They were never consciously a factor in our judgments.

The rôle which vision normally plays in compensation for oscillation is not so easily obtained as one would ordinarily suppose. Our experiments demonstrate that visual fixation upon various features of the environment, with attempts at compensation for oscillation of the platform, does not always produce adequate compensation. In order to compensate most accurately, it was necessary to see both the motionless environment and the recording lever. A and B in Fig. 4 show a high adequacy of compensation. In this case the subject sighted past the compensating lever to the floor. In the latter half of C and D the subject looked through a hole in a mask, with the right eye focused on a radiator while a pointer moved with the rotating

* Figures 4, 15, 16, 17, and 20 were manufactured by first tracing the records. While they show the general nature of the response, they fail to show the uniformity of the platform curves and time lines.

platform across his line of regard. In the latter case, the subject could not see his arms nor the compensating lever, and the compensation was less adequate. Fig. 4 illustrates very clearly the difference between reactions under the two visual situations. Although A and B represent records under the most favorable visual conditions, the upper or compensating line is not a straight line. The small irregularities are pulse waves; those which follow the periods of oscillation of the platform are due to the fact that the head was held rigid and oscillates with the platform, thus causing a change in the visual parallax, so that the apparent excursion of the platform is not as great as the real excursion. In the main experiments visual data were eliminated by closing the eyes and blindfolding the subject.

The rôle that audition might have played in the perception of oscillation at the amplitudes and frequencies we used was not experimentally investigated. The question is interesting, especially in rectilinear oscillation, but it lay beyond the scope of the present inquiry. The undesired effect of audition on the perception of motion was reduced to a minimum by producing a constant noise of sufficient intensity to mask all other noises in the experimental room. The masking noise was produced by an electric fan striking on paper. Since the fan was located on the rotating platform the noise always remained in the same direction from the subject. The subject's head was always held in position by a head rest. This practically eliminated pulse thrusts and accidental movements, facilitating the discrimination of the direction of rotation and restricting the stimuli to the same canal systems.

The cutaneous, kinaesthetic, and organic sensory data could not be eliminated or directly masked. We could detect nothing introspectively in *rotary* oscillation which might be attributed to these receptors, even in the most rapid speed used. The rôle of kinaesthetic factors in *rectilinear* oscillation, at or near its threshold, is a very different matter and will require special discussion later on.

Preliminary experiments indicated that a range of angular displacements in rotary oscillation on the center from 1 to 4 degrees, and a range of average velocities from .25 to 1 degree per

second, would include both subliminal and supraliminal stimuli. Analogous values for rectilinear oscillation range from 2 to 6 cm., and from 0.5 to 2 cm., per second. In rotary oscillation at various distances from the center, angular displacements of 0.7 to 3.7 degrees and average velocities of 0.35 to 1.4 degrees per second were used.

Under conditions of sine-wave oscillation the actual speed varies from zero degrees (or cm.) per second at the beginning and end of the swing to two times the average velocity of the complete oscillation at the center of the swing. If the average speed of the platform were one oscillation in one second, or two degrees (or cm.) in one second, the extremes of speed would be zero degrees (or cm.) at the beginning and end of the swing and four degrees (or cm.) per second at the center of the swing. The acceleration in cm. per second at the point of attachment of the driving rod, for any given angle after the onset would be $(\frac{2\Pi r}{P})^2$ r cos*a*. Where r equals the radius of the driving wheel in cm.; P equals the time for one oscillation in seconds and *a* any given angle. At the center of each half-oscillation the velocity is greatest and the acceleration is zero. At the beginning and end of each half-oscillation the velocity is least and the acceleration is greatest.

To ascertain the limens in rotary and rectilinear oscillation, it is necessary to systematically vary the amount of angular displacement and rectilinear displacement together with the frequency of oscillation. In other words, the frequency of oscillation determines the frequency of stimulation, whereas the combination of frequency and amount of displacement determines the intensity and duration of each stimulus.

In the effort to determine the relative thresholds of vestibular and extra-vestibular receptors in rectilinear oscillation we secured data under five different experimental conditions—namely, sitting with the back and head supported on rests, sitting with the back and head free from the rests, sitting with the head, chest, and abdomen tightly strapped to the chair and rests, standing unsupported facing at an angle of 90° to the direction of oscillation,

and standing unsupported facing in the direction of oscillation. In the first sitting position, supposititious vestibular, pressure, and organic data were admitted while visual, auditory, and kinaesthetic data were excluded. In the second sitting position, vestibular, kinaesthetic, organic, and pressure data were admitted with only vision and audition excluded. In the third sitting position, vestibular and organic data were admitted with all the rest reduced to a minimum. In the standing positions, sensory data from kinaesthesis were emphasized with pressure, vestibular, and perhaps organic data admitted.

The kinaesthetic data in the standing positions seemed to arise mainly from the feet, ankles, and legs; whereas in the sitting position with body and head free from the rests, the kinaesthetic data seemed to arise from the hips, back, and occasionally from the neck. The vestibular data are complicated by rotation of the head due to the swaying of the body. Thus, in rectilinear oscillation in the standing positions we not only have vestibular data arising from movement in straight lines, but also from rotary movement about the ankles or hips as the axis. It seems impossible to permit free movement of the head or body without including rotation.

A further possible complication of the data arises from movements of respiration. In ordinary sitting postures respiration has been shown to produce slight rotation-movements of the head. If these rotation-movements are of sufficient magnitude, there is reason to believe that the canals in planes aside from the horizontal will be rhythmically excited. With the head on the rests, the rotation movements caused by respiration are greatly reduced in amplitude. Dodge demonstrated these movements by optical means and measured them photographically. A rough estimate of their amplitude can be obtained by attaching a recording lever fifty-six cms. long to the side of the head. If a meter stick is held upright close to the farther end of the lever, the excursion of the lever caused by respiration can be read directly in mm. on the meter stick. With the head on the rest, the vertical movement of the distal end of the lever was not over 1 mm., or about 0.1 of a degree, for either subject during normal

respiration. The horizontal movements were also mostly less than 0.1 of a degree. This small range of rotation-movement in the average time for one inspiration or expiration is far below the rotation threshold and indicates that respiration probably did not play any significant rôle in our experiments when the head-rests were used.

The specific precautions taken in the experiments in both rotary and rectilinear oscillation are as follows:

1. Held breath at full inspiration (40 seconds), to eliminate respiratory movements. This was probably unnecessary and was required only for threshold determinations.
2. Order of changes in stimulus forms unknown to the subject.
3. Vibration of platforms reduced to minimum to eliminate secondary cues to oscillation. If vibration was felt, it was reported and immediately corrected.
4. Eyes properly covered and closed, except in experiment of visual perception in rotary oscillation.
5. Masking noise, to eliminate the effect of noises in experimental room. Source of masking noise was located on the platform.
6. Two periods of no physical movement in each series of oscillations.
7. Hands and arms anchored in sitting position in rectilinear oscillation with fingers free.
8. Rest period between experiments.
9. Subject required to report any secondary cues to oscillation.

Other precautions and conditions varied with the problems. The subject understood the nature of all the experiments, but never knew their order. He was practiced in compensatory reactions until they seemed automatic. In each arrangement the experimental series was repeated on ten different days or twice each day for five days. Much the same precautionary measures were taken in the experiments with the subject at various distances from the axis of rotation. The subject was however permitted to breathe naturally throughout these experiments due to the length of some series.

In view of the fact that preliminary experiments indicated alternations between rotary and rectilinear translation in the perception of motion when one is oscillated at various distances from the axis, we decided to combine the rotary and rectilinear components in various proportions. In terms of the average acceleration value evoking 50% right responses for the two subjects, the position where the rectilinear component was predominant

we computed to be 326 cm. from the axis; where the two components were equal we computed to be 217 cm. from the axis, and where the rotary component became predominant was 109 cm. Due to the rather large differences in vestibular sensitivity between the two subjects, the calculated distances from the axis were only approximately correct in combining the desired proportions of the two components.

F. Restatement of the Experimental Problem

Our fundamental problem concerns the interplay of various more or less elementary processes in the variability of human response to recurrent stimulation of known intensity, frequency, and duration. For reasons which we have already discussed we chose the vestibular mechanism, stimulated by oscillation. Before the fundamental problem could be attacked, however, it seemed necessary to study some of the details of the system that we intended to exploit. In this preliminary study we met the familiar experience—namely, as the experiments progressed more and more partial problems presented themselves for solution. An investigation of the interplay of refractoriness, adaptation, after images, centrally aroused images, negative effect of faint stimuli, summation of stimuli, and neuro-muscular rhythms presupposes as much knowledge as practicable of the interacting factors.

Similarly, the fundamental problem demands the utmost purity of the vestibular data, free from the reënforcing and inhibiting effects of uncontrolled data from other receptor fields, such as vision, audition, the cutaneous and kinaesthetic senses. But the effort to eliminate them required knowledge of their relative thresholds and their relative effectiveness in the perception of both rotary and rectilinear oscillation.

Where it is not possible to eliminate conflicting data, they must be reduced to ineffective intensity, or masked by indifferent inhibiting stimuli of the same order, with consequent relative emphasis on the experimentally significant factors. Our immediate experimental program, consequently, came to include an analysis of the various factors involved in three main modes of

stimulation—namely, passive rotary oscillation of the subject at the axis, passive rectilinear oscillation, and passive rotary oscillation with the subject at different distances from the axis of rotation. The last mode is practically the universal form of actual passive translation through space. Even with the most exacting technique it is never possible to free rotary motion from a direct translation component, since one cannot place the entire body exactly over the axis of rotation, not even both ampullae of corresponding canals. Similarly, the purest possible rectilinear translation is usually contaminated by one or more rotary factors.

G. Method of Treatment of the Graphic Records of Response

The experimental data will be clearer if the meaning of the objective records and the method of treatment of these records are considered first.

The recording levers from the two platforms produce a sinusoidal curve record on the smoked drum. In rectilinear oscillation the amplitude of this curve is equal to the actual displacement of the platform. Thus a two cm. movement of the platform produced a two cm. excursion of the lever pointer on the smoked drum. In rotary oscillation one cm. on the curve represents one degree of angular displacement. When the platform is oscillating and the kymograph running, a curve similar to the solid line in Fig. 5 is obtained. This curve represents one complete oscillation of the platform.

The curves of the compensating manual response are not as regular as shown in the schematic diagram. However, the dotted lines will serve to indicate the five major possibilities of the response. This scheme was adapted empirically to facilitate the reading of the records. The height of the response curve is read in millimeters and indicates the direction and adequacy of the response. The position of the response curve relative to the platform curve is ascertained by reading lengthwise to the record and represents the kind of compensatory response. In all the

records, with very few exceptions, the response curves were easily placed in one of the five categories of compensation—namely, partial, *Pa,* negative, *N,* zero, *0,* perfect, *Pe,* and over compensation, *Ov.*

In our fundamental experiments the compensating response was *perfect* if the record is a straight line on the smoked drum; it was *partial* if the response curve is less than the platform curve in amplitude. The amount of compensation is the difference between the compensation curve and the platform curve. In case the compensation was *negative,* the compensation curve is greater in amplitude than the platform curve and the amount of negative compensation is the difference between the two curves; in over compensation, the compensation curve extends in the opposite direction from that of the platform and the amount is obtained by adding the amplitude of the response curve to the amplitude of the platform curve. In case the compensation is *zero,* the compensation curve is similar to the platform curve.

Simple formulae can be derived from the different kinds of compensation as a short cut in ascertaining the adequacy of compensation. By adequacy of compensation we mean how well the subject compensates by holding his hands and arms or fingers still in space, or the approximation of the response curve to a

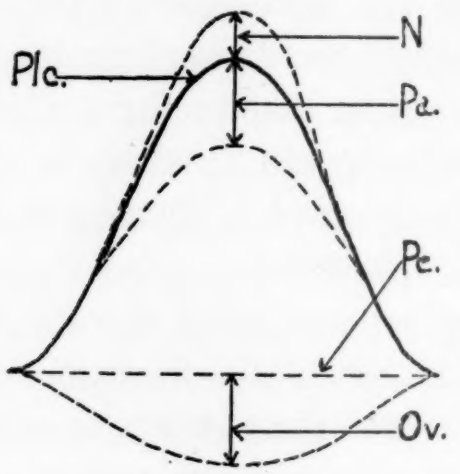

FIGURE 5. Schematic diagram of the objective record of one complete oscillation of the platform (solid line), and the five major possibilities of the accompanying compensating manual response (broken lines). Plc—platform curve; N—negative compensation; Pa—partial compensation; Pe—perfect compensation; Ov—over compensation.

straight line. The formula for adequacy of compensation with the definitions of the symbols, is as follows:

$$\text{Adequacy of compensation, } C = \frac{\Sigma A - \Sigma (p+n+ov+o)}{\Sigma A}$$

A = Amplitude of platform curve

p = Amplitude of partial compensation curve
n = Amplitude of negative compensation curve
ov = Amplitude of over compensation curve plus platform curve
o = Amplitude of zero compensation curve
Σ = the sum

It may not seem justifiable at first to consider each half-oscillation as a single stimulus, because theoretically each period of acceleration or of deceleration may be a stimulus, thus two stimuli may occur in each half-oscillation. A true compensatory movement to the acceleration would be in the reverse direction from that of the accelerated body while a true compensatory movement to the deceleration would be in the same direction as that of the decelerated body, but farther and faster. Consequently, we would expect the response curve to show a slowing-down during acceleration and a speeding-up during deceleration. It will be seen from the experimental data that this is not usually the case in rotary oscillation. Apparently the response was made to each half-oscillation as a single stimulus. However, in rectilinear oscillation there is evidence of occasional speeding-up of the compensatory reactions on the deceleration phase; these we have interpreted as negative reactions. Such negative reactions seem to occur more often with faint stimuli. If the negative reactions were to be taken as the correct response on the deceleration period, the vast majority of reactions that occur on the deceleration period would have to be termed wrong responses. This would distort the facts and prevent an adequate interpretation of the data, because the majority of reactions occur to each half-oscillation as a single stimulus.

Empirical justification for this interpretation is contained in Dodge's " Habituation to Rotation," (14) where the movements of the eyes during oscillation show that compensatory eye movements are always in the same direction during both the acceleration and deceleration periods of each half-oscillation.

IV. EXPERIMENTAL DATA

A. Passive Rotary Oscillation with the Subject at the Axis

In the effort to factor out the relative psycho-physiological effectiveness of the physical properties of harmonic motion, various combinations of frequencies and amplitudes of oscillation were chosen to give equal average angular velocities and accelerations, with varying frequencies; and equal frequencies with varying average angular velocities and accelerations. For example, sine-wave oscillations giving 4 degrees angular displacement in 4 seconds have an average angular velocity of 1 degree per second and an average angular acceleration of the ampullae of 0.0832 cm. per second. They have the same average angular velocity as 2 degrees in 2 seconds, but are twice as great as the 2 degrees–2 seconds combination in terms of average acceleration. Oscillations of 2 degrees in 2 seconds, and 8 degrees in 16 seconds, are equal in average angular acceleration (.04159 cm. per second), but differ in frequency and average angular velocity. Thus, the frequency, angular velocity, and acceleration may be systematically varied, while the form of oscillation remains constant, approximating a sine-wave.

A limitation of this particular stimulation form lies in the fact that the duration of the stimulus is not easily varied without varying the frequency. In continuous sine-wave oscillation the longer the time between the recurrence of any given phase, the longer the duration of the stimulus wave, and vice versa. Thus, the duration of stimulation varies inversely as its frequency.

Data obtained from preliminary experiments with amplitudes ranging from 0.2 to 8 degrees and durations from 1 to 80 seconds per oscillation, showed that amplitudes of 1, 2, and 4 degrees with frequencies of 2, 4, 8, 16, and 32 seconds included subliminal and supraliminal stimuli for both subjects.

The following table gives the nine combinations of frequencies

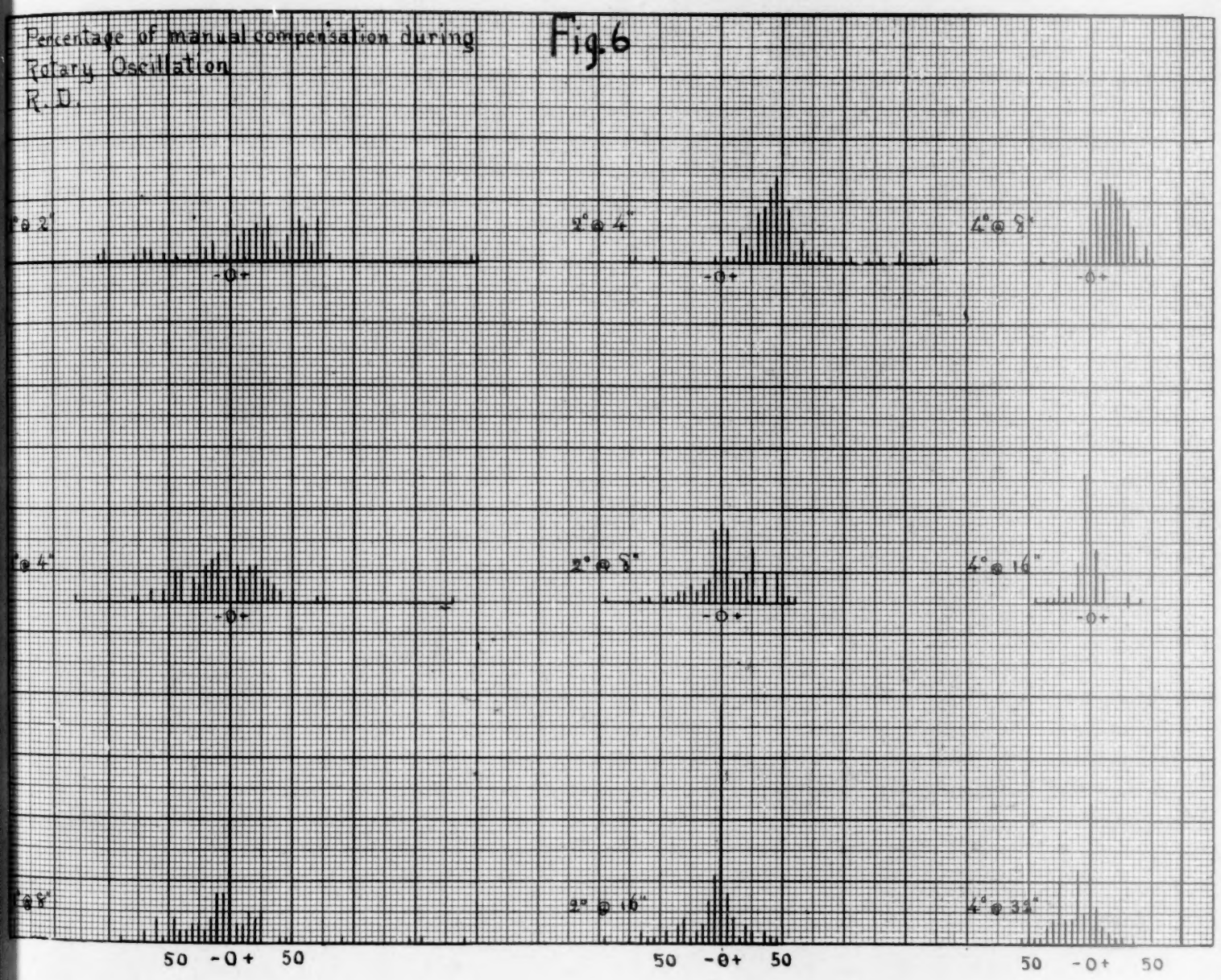

FIGURE 6. RD. Distributions of percentages of manual compensation during rotary oscillation with the subject at the axis.

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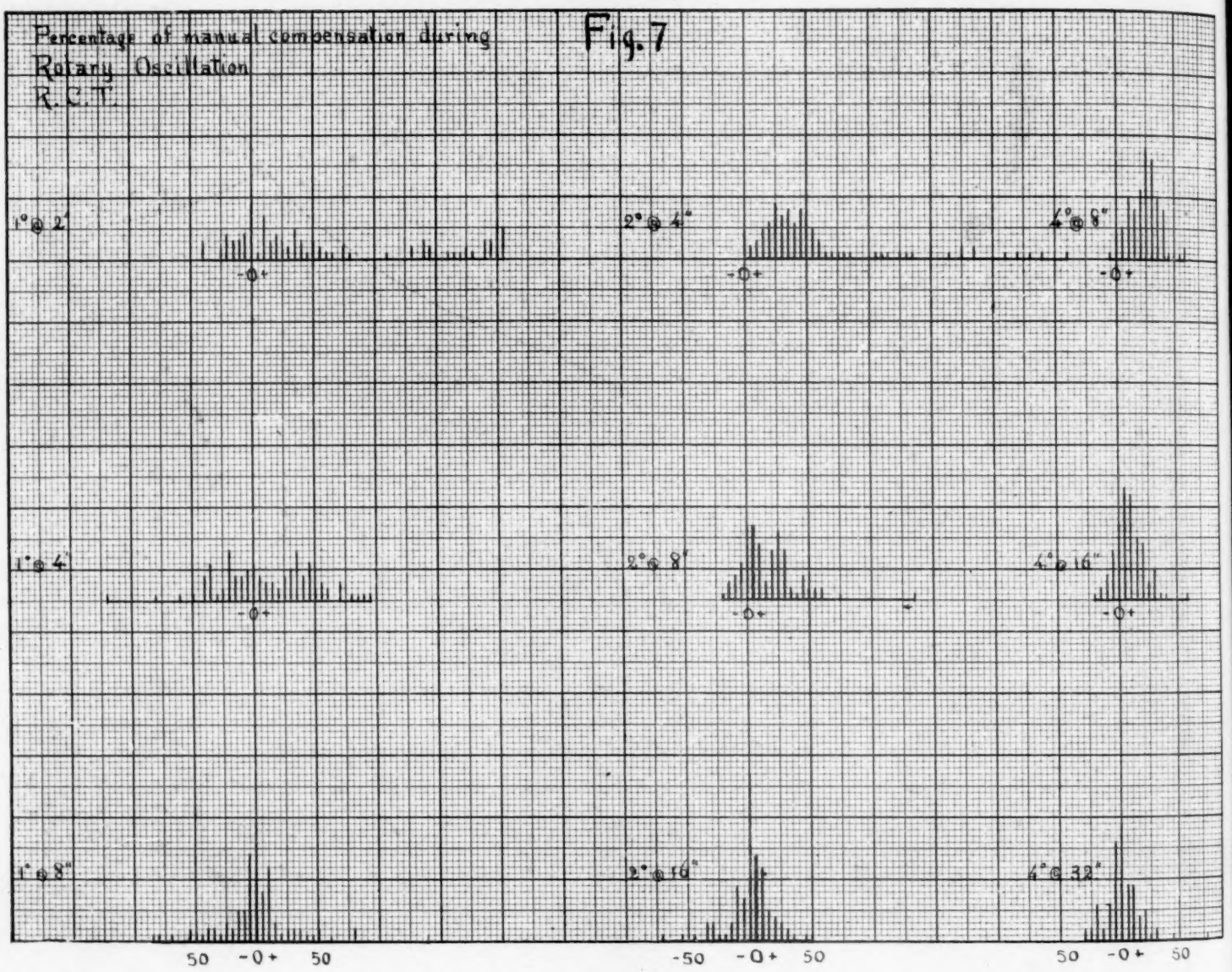

FIGURE 7. RCT. Distributions of percentages of manual compensation during rotary oscillation with the subject at the axis.

and amplitudes, the corresponding average velocities, and the average accelerations of the bony canals.

Amplitude Degrees	Total Excursion Degrees	Frequency and Duration Seconds	Average Velocity Degrees per Second	Average Acceleration Cm. per Second
1	2	2	1	.0416
2	4	4	1	.0832
4	8	8	1	.1664
1	2	4	0.5	.0104
2	4	8	0.5	.0208
4	8	16	0.5	.0416
1	2	8	0.25	.0026
2	4	16	0.25	.0052
4	8	32	0.25	.0104

Two trained subjects participated regularly in these experiments. They will be designated respectively as RD and RCT.

1. *The Distributions of Compensations*

The distributions of the percentages of manual compensation to rotary oscillation, with the subject's head at the axis, for nine different stimulus combinations are given in Figures 6 and 7 for RD and RCT, respectively. Negative compensatory responses, *i.e.*, compensations in the wrong direction, are distributed on the left side of zero, and positive compensatory responses (partial and over) are distributed on the right. The number of negative and zero responses vary inversely with the average velocity of motion for both RD and RCT for all three amplitudes.

The variation in percentage of correct compensation decreases slightly with decreasing velocities in the case of RD. There is little change in this respect in the case of RCT. On the whole, oscillations of one degree amplitude produced the greatest variability for both subjects. The extreme variability in this case is due to the magnitudes of the negative and over-compensatory responses. As the duration of the oscillation increased, *e.g.*, in the 4 degrees amplitude, the variability decreased and the distributions approach the normal.

The main fact disclosed in these distributions of percentages of voluntary manual compensation is that, as the average velocity of oscillatory motion at each amplitude increased, the adequacy

of compensation increased. There is a striking uniformity in this respect for all three amplitudes in the reactions of both subjects. This may be expressed as follows. Within our experimental limits the faster the rotary harmonic motion the better the perception of its direction and amplitude and the more nearly adequate the consequent manual compensation. The proportionality is, however, not simple, and we must presently discuss the relative importance of the various physical characteristics of harmonic motion and perhaps also of other factors in the perception of oscillatory rotation.

In addition to the main facts there are several noteworthy details in these distributions. In the first place, they show how inadequate the concept of threshold would be when applied to compensatory reactions to stimuli of various low intensities if all reactions are adequately recorded and accounted for. Limen or threshold, in the strict and original sense, if the figure of speech means anything in compensatory behavior, signifies a line separating two different orders of fact, one in which there is no compensation consequent to the physical stimulus, and the other in which compensation occurs, emerging at the threshold value. Our facts cannot be interpreted according to this figure of speech. They are better expressed by distributions rather than by mere central tendencies. Below the supposititious line of threshold values lies an orderly series of events more or less analogous with that above it. With more intense stimuli the series includes a few cases of true compensation most nearly approaching theoretical adequacy, many cases of less adequate compensation, and several cases of still less adequate response, sometimes including a few negative compensations or reactions in the wrong direction in approximately normal distributions. With decreased intensity of stimulation the mode shows less and less adequacy with an increasing number of negative compensations. At some intensities the negative values balance or overbalance the positive; at still lower values the number of failures to compensate becomes increasingly conspicuous, with a fairly even distribution of slight positive and negative compensations. Nowhere is there a sharp break in the series of events, nowhere an emergence of compensa-

tion corresponding to a real threshold. Negative compensation is not an exceptional or peculiar form of reaction, but a regular phenomenon, corresponding in the orderly series of events in the case of weaker stimuli to the less adequate compensation in the case of stronger stimuli.

Somehow or other, in any adequate understanding of reaction phenomena there must be included the negative compensation, with a parallel consciousness of movement in a direction the reverse of that which corresponds to the physical stimulus. We did not overlook several easy but inadequate interpretations of negative compensation. For example, pure chance as to the direction of compensation in the absence of any real clue would favor an even number of negative and positive compensations. The orderly progression of the series and their systematic relationship with various intensities of stimulation make a hypothetical reference to chance a very weak scientific expedient. It would be even less satisfactory to suppose that certain intensities of stimulation favored a motor confusion of compensatory and negative compensatory reaction. The subjects were carefully trained before the series started, and the sequence of intensities was carefully arranged to prevent any place values in the experimental series. The order of the intensities was never twice alike. Moreover, motor confusion would be expected to depend on the integration of response rather than on the intensity of stimulation. We do not venture an interpretation of this data. At present we would merely call attention to certain facts that emphasize the arrangement of subthreshold phenomena and the prominent place in that arrangement of the negative effect of faint stimuli. There are indications that these negative effects are not unique phenomena of manual compensation. Newhall and Dodge (**15**) have called attention to them in one phase of the visual process. If they prove to be general, as seems probable, they promise to throw light, not only on the limits to the spread of neural excitation, which with increasing decrements might reach a value producing negative reactions at the periphery of any neural system, but also on such diverse mental phenomena as the close approximation of some apparently contradictory phe-

nomena of consciousness. Another less far reaching and probably less debatable aspect of our plotted data is the indication that frequency and intensity constitute relatively independent factors in vestibular stimulation.

The data from which these distributions were plotted are summarized in the following tables. The daily variation in the percentage of right responses to rotary oscillation, with the subject at the axis, for the three amplitudes for RD and RCT is shown in Tables 1 and 2. It will be seen from the interpolated 50%

TABLE 1

RD. Percentages of right responses in compensation for rotary oscillation with the subject at the axis for all three amplitude-frequency combinations. Average velocity is given in degrees per second; average acceleration of the ampullae is given in cm. per second.

Amplitude.....	One Degree			Two Degrees			Four Degrees		
Average velocity....	1.0	.5	.25	1.0	.5	.25	1.0	.5	.25
Average acceleration	.0416	.0104	.0026	.0832	.0208	.0052	.1664	.0416	.0104
Days									
1.....	100	50	40	100	50	30	60	10	0
2.....	90	20	20	100	35	5	80	20	25
3.....	60	60	10	65	50	50	80	10	0
4.....	80	50	50	90	60	30	100	30	50
5.....	60	50	60	90	50	40	90	67	37
6.....	80	51	10	100	80	0	90	10	11
7.....	70	30	50	100	60	10	89	30	38
8.....	50	50	0	100	30	45	55	0	12
9.....	70	40	40	90	70	40	100	10	25
10.....	100	20	0	100	56	30	90	40	11
Average.....	76	42	28	94	54	28	83	23	21

Interpolated values giving 50 per cent right responses (traditional limen)

	One Degree	Two Degrees	Four Degrees
Average velocity	.62	.46	.74
Average acceleration	.0177	.0176	.0978

Average velocity for all three amplitudes..... .61 degrees per second
Average acceleration for all three amplitudes..... .0444 cm. per second

values that the amplitude of 2 degrees at periods of 4, 8, and 16 seconds per oscillation is the most effective of the three in arousing the vestibular system. For this amplitude the average velocity yielding 50% right responses is 0.46 degree per second for RD, and 0.25 degree per second for RCT. The corresponding average acceleration value is 0.0176 cm. per second for RD, and 0.0051 cm. per second for RCT. The average for all three amplitudes is 0.61 degree per second, and 0.0444 cm. per second, respectively, for the average velocity and average acceleration in the case of RD, and 0.35 degree per second and 0.0108 cm. per second for

TABLE 2

RCT. Percentages of right responses in compensation for rotary oscillation with the subject at the axis for all three amplitude-frequency combinations. Average velocity is given in degrees per second; average acceleration of the ampullae is given in cm. per second.

Amplitude.....	One Degree			Two Degrees			Four Degrees		
Average velocity....	1.0	.5	.25	1.0	.5	.25	1.0	.5	.25
Average acceleration	.0416	.0104	.0026	.0832	.0208	.0052	.1664	.0416	.0104
Days									
1.....	100	20	22	100	40	30	85	90	40
2.....	50	70	50	88	80	45	89	88	58
3.....	80	40	50	100	67	28	88	100	44
4.....	78	60	30	100	80	67	100	70	24
5.....	70	80	60	100	76	50	90	67	36
6.....	90	50	20	80	90	70	100	70	25
7.....	40	88	30	100	100	67	100	88	33
8.....	60	22	0	100	100	50	100	63	33
9.....	60	40	75	100	60	50	100	80	25
10.....	90	70	20	100	78	50	100	60	78
Average.....	72	54	36	97	77	51	95	78	40

Interpolated values giving 50 per cent right responses (traditional limen)

	One Degree	Two Degrees	Four Degrees
Average velocity	.45	.25	.36
Average acceleration	.0087	.0051	.0186

Average velocity for all three amplitudes..... .35 degrees per second
Average acceleration for all three amplitudes..... .0108 cm. per second

average velocity and average acceleration in case of RCT. In comparing these values with the thresholds previously published by Dodge* it should be remembered that oscillatory and occasional rotation are quite different stimulation forms. The present values are not presented as corrections of the previous approximations. They are probably entirely new data.

2. *Relations Between the Percentages of Right Responses, Average Velocity, Average Acceleration and Frequency of Stimulation*

The relation between the percentages of right responses and the average velocity for RD and RCT in degrees per second for three different frequencies is given in Figure 8, A and B. The curves clearly show that the greater the average velocity of oscillation the more adequate the response, with the single exception of the 8 seconds frequency in the case of RD. Fig. 8, C and D, show a small but fairly regular increase of right responses in the middle frequency at all velocities. The exceptions are few and inconclusive. This slight advantage of the middle frequency

* *Op. cit.*

is difficult to interpret. Doubtless the main significance of these figures is to show the relative unimportance of frequency in comparison with average velocity.

The relation between the percentages of right responses and the average acceleration with frequency constant at 4, 8, and 16

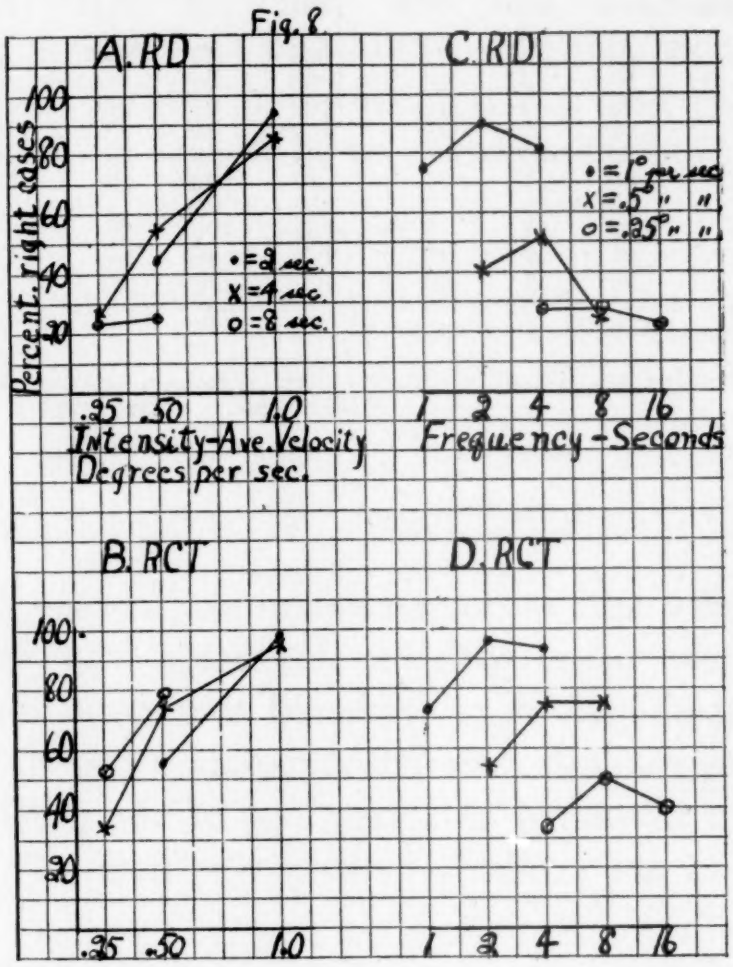

FIGURE 8. *A* and *B*, relation between the percentage of right responses and the average velocity. *C* and *D*, relation between the percentage of right responses and frequency of stimulation.

seconds is shown in Fig. 9, A and B. These curves clearly indicate that acceleration is an important factor in vestibular stimulation and furnish a suggestive contribution to psycho-physiological fact. Due to the fact that the relation between velocity and acceleration is somewhat complicated in harmonic motion, it seemed expedient to express the data in terms of both variants. Fig. 9, C and D, show the relation between the percentage of right reactions and the frequency, with average acceleration constant at .0104 and .0416 cm. per second. Frequency seems to be more significant for subject RD than for RCT.

The averages of the percentages of the four different categories of compensatory responses, the average of the percentages of right responses and the percentages of adequacy of compensa-

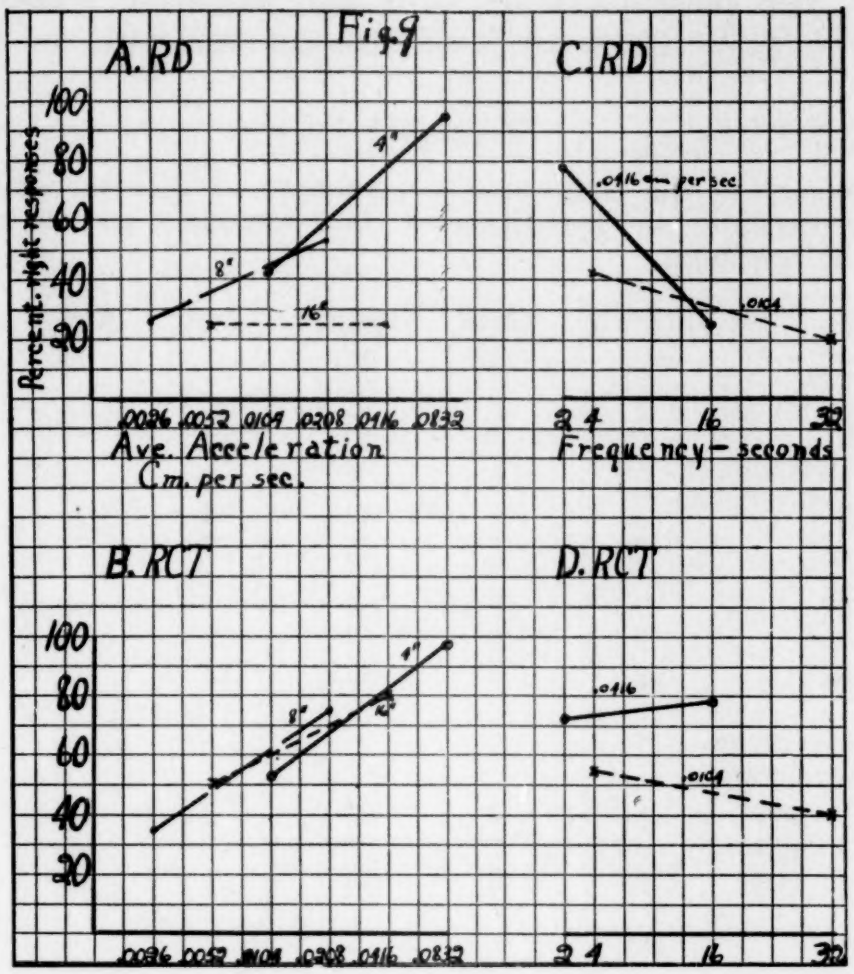

FIGURE 9. *A* and *B*, relation between the percentage of right responses and average acceleration. *C* and *D*, relation between percentage of right responses and frequency of stimulation, with constant average acceleration.

tory responses are given in Tables 3 and 4. The values represent averages of ten successive repetitions of the experimental series. Each table is summarized in terms of average velocity and average acceleration. For an explanation of the various kinds of compensatory responses the reader is referred to Fig. 5. The column designated "Total right" in Tables 3 and 4 represents the sum of the *over* and *partial* compensatory responses. The *negative* and *zero* compensatory reactions are considered as wrong responses. The column designated "adequacy" represents the approximation of the compensatory responses to the speed, extent, and direction of movement of the oscillating platform. The

tables again show that the greater the average velocity and acceleration the larger the percentage of partial and over compensatory responses, and the less the average velocity and acceleration the greater the percentage of zero and negative compensatory responses.

TABLE 3

RCT. Summary of the percentage for ten days of the four categories of compensatory responses, the percentage of right responses, and the percentage of adequacy of responses.

Stimulus		Partial	Over	Negative	Zero	Total Right	Adequacy
2° in 2″		73	3	21	3	76	17
2° in 4″		40	2	50	7	42	—7
2° in 8″		24	4	47	25	28	—7
4° in 4″		85	9	5	1	94	39
4° in 8″		53	1	42	4	54	7
4° in 16″		26	1	46	27	27	—6
8° in 8″		83	0	14	3	83	16
8° in 16″		23	0	58	19	33	0
8° in 32″		21	0	66	13	21	—11
Average Velocity	Average Acceleration						
1.0	.097	81	4	13	2	84	24
0.5	.0243	39	1	50	10	40	0
0.25	.0061	27	2	53	21	29	—8

TABLE 4

RCT. Summary of the percentages for ten days of the four categories of compensatory responses, the percentage of right responses, and the percentage of adequacy of responses.

Stimulus		Partial	Over	Negative	Zero	Total Right	Adequacy
2° in 2″		39	33	19	9	72	18
2° in 4″		53	1	40	6	54	13
2° in 8″		34	2	45	19	36	—1
4° in 4″		77	20	0	3	97	35
4° in 8″		76	1	17	6	77	17
4° in 16″		51	0	37	12	51	0
8° in 8″		95	0	5	0	95	26
8° in 16″		78	0	20	2	78	9
8° in 32″		40	0	44	16	40	1
Average Velocity	Average Acceleration						
1.0	.097	70	17	8	4	88	26
0.5	.0243	69	1	26	5	70	13
0.25	.0061	41	1	42	16	42	0

A graphic representation of the percentage of right responses and the percentage of adequacy is given in Figure 10, A and B. The abscissa represents the percentages, the ordinate the average velocities in degrees per second. The curves have the same general slope for both subjects and are closely similar for all three ampli-

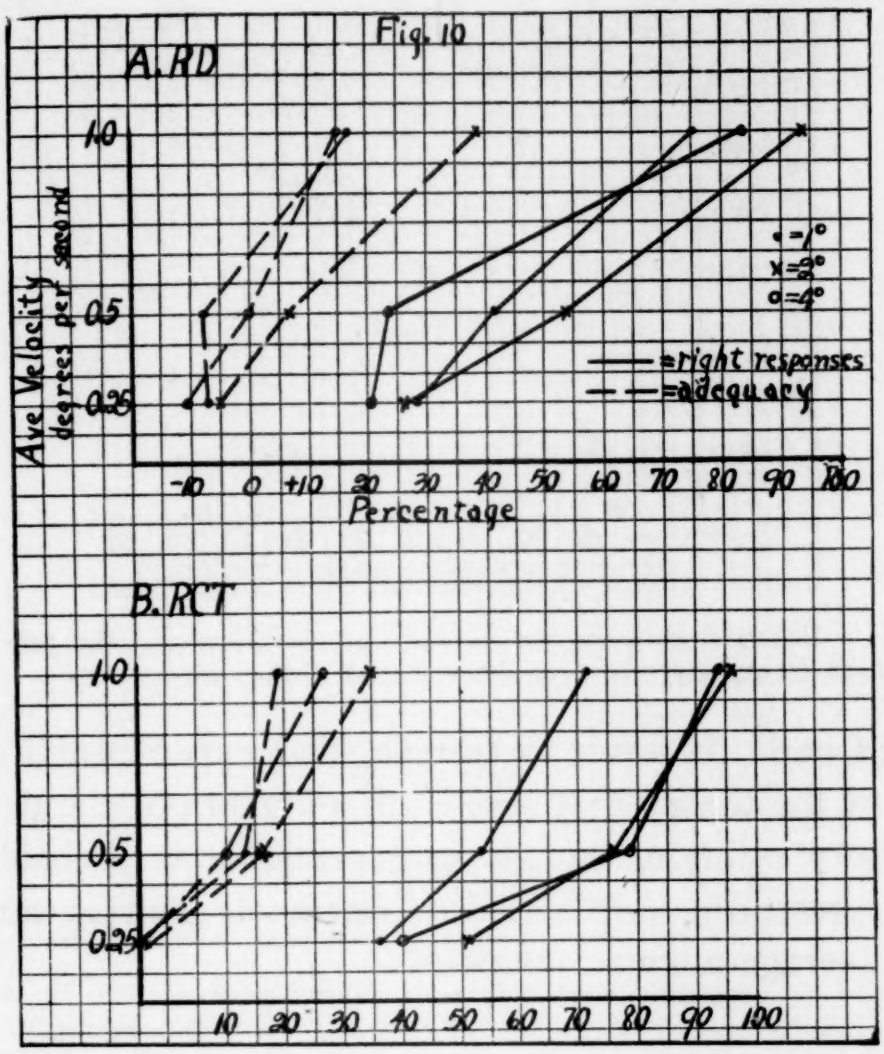

FIGURE 10. *A* and *B*, relations between the percentage of right responses, the average velocity and the percentage of adequacy for all three amplitude-frequency combinations.

tude-frequency combinations. The adequacy of responses has a minus value in the case of RD, at the low intensities, due to the large number of negative responses.

In view of the traditional importance of acceleration as the fundamental factor in vestibular stimulation, a curve showing the relation between the average acceleration of all three amplitudes and the percentage of right responses irrespective of fre-

quency may be useful. Such a curve is given in Figure 11, A and B, for RD and RCT. The curves are surprisingly uniform considering the large temporal differences involved in the experimental series. The almost rectilinear relationship between acceleration and the percentage of right responses is too consistent

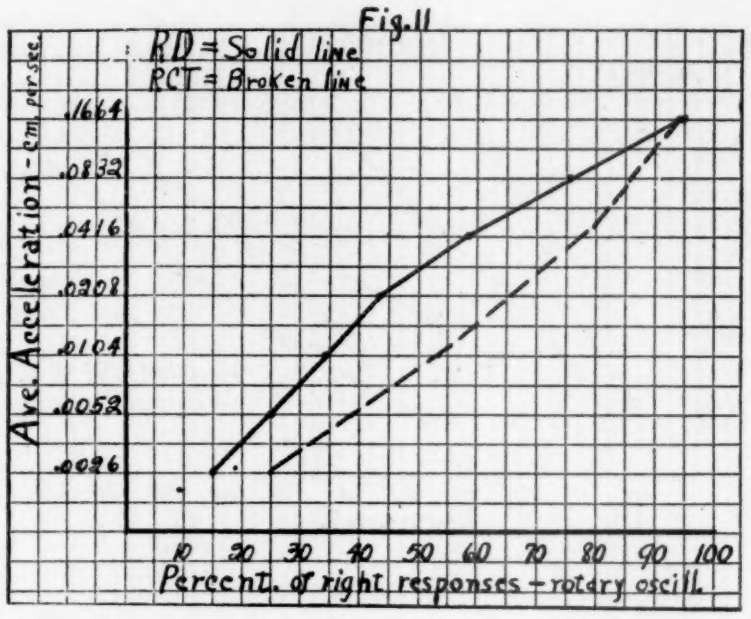

FIGURE 11. Relation between the average acceleration and the percentage of right responses irrespective of frequency for all three amplitudes.

to be accidental. It seems to furnish clear experimental evidence in favor of the theory that acceleration conditions the perception of oscillatory rotation, though no grave error is probably introduced in presenting our series of harmonic motion stimuli in terms of average angular velocities.

3. *Variation in Velocities Evoking* 50% *Right Responses, Adequacy of Compensation, and in Reaction Times Consequent to Beginning and Successive Half-Oscillations*

The daily variation in the average velocities of rotary oscillation which elicit 50% right responses for the three stimulation amplitudes is given in Figure 12, A and B. The abscissa represents the days or successive trials of the experiments; the ordinate represents the average velocity in degrees per second.

The two degree amplitude shows the least variability of the threshold for RD, ranging from .25 to .64 degrees per second; while the 4-degree amplitude has the greatest variability, which

ranges from .25 to .94 degrees per second. In the case of RCT the 4-degree amplitude shows the least variability, ranging from .18 to .39 degrees per second; while the 1-degree amplitude shows the greatest, ranging from .21 to .75 degrees per second. The three amplitudes do not vary alike from day to day for either sub-

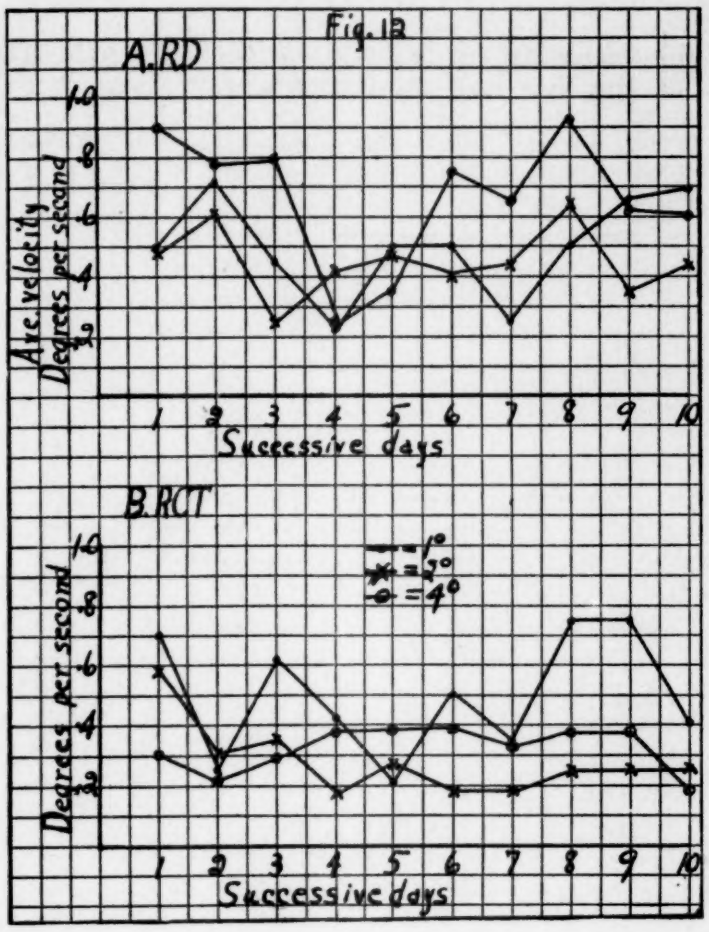

FIGURE 12. *A* and *B*, daily variation in vestibular sensitivity to rotary oscillation in terms of average velocities evoking 50 per cent right responses, for all three amplitudes.

ject. Our data seem to indicate that not only is there a daily variability in vestibular sensitivity, but variability from moment to moment as well, suggesting the interaction of other factors beside the objective stimuli.

Successive variations in percentage of adequacy and kind of compensation from oscillation to oscillation are shown in Figure 13, A and B.

Each point in these curves represents the manual compensation for one complete oscillation. Each break in the curves represents an interval of one day. The horizontal line represents zero com-

pensation; above this line is the percentage of positive compensation; and below, the negative compensation. The stimulus which evoked about 50% right responses was used as standard for each subject, viz., 2 degrees in 8 seconds for RD and 2 degrees in 16 seconds for RCT. It is obvious from these curves

TABLE 5

Distribution of the incidence of reactions within the first half oscillation. Units of the first half-oscillation curve given in mm.

Curve Units MM.	Frequency of Reactions RD	RCT
0		
1	10	2
2	2	12
3	4	4
4	8	8
5	12	16
6	4	16
7	16	4
8	24	12
9	12	4
10	4	4
11	8	8
12	2	4
13	2	4
14	3	4
15	1	4
16	0	8
17	4	4
18	1	8
19	3	1
20		
Total	120	127

that response to stimuli of constant intensity and frequency varies conspicuously in the nature and adequacy of the reactions from stimulus to stimulus, from record to record, and from day to day. In the short periods of stimulation used in these experiments no clear or consistent rhythmic tendencies in the variability of responses are apparent. That is, when a response to one oscillation is positive, the response to the next oscillation may be negative, zero, or positive. There is no apparent basis for predicting what the next response will be. More intense stimulation produces much the same sort of variability in the adequacy of the response, but if the stimulus is intense enough the compensation remains consistently positive.

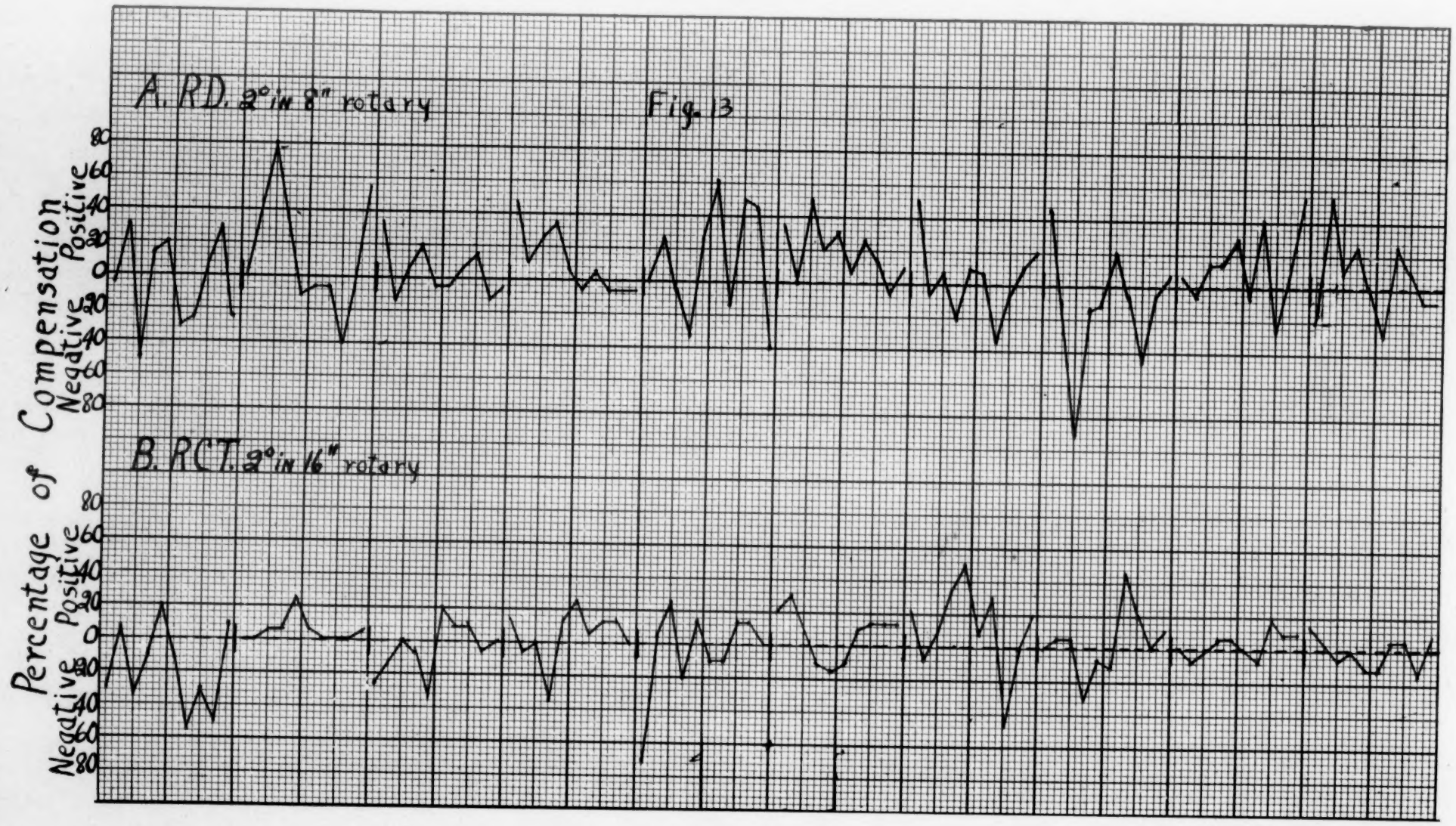
A. RD. 2° in 8" rotary
Fig. 13
Percentage of Compensation
Negative Positive
80 60 40 20 0 20 40 60 80
B. RCT. 2° in 16" rotary
80 60 40 20 0 20 40 60 80

FIGURE 13. *A* and *B*, temporal variation in the percentage of adequacy and the kind of compensation from oscillation to oscillation and from day to day.

Notwithstanding the irregularity of the curves, it will be noted that in the series of responses there are suggestions of wave-like periods of alternating increased and decreased excitability as the reactions vary from partial through zero to negative compensation. While further experimentation is necessary to check this

TABLE 6

The incidence of delayed reactions at varying speeds of oscillation.

Stimulus	The Percentage of Reactions Requiring More than One Half-Oscillation		The Percentage of Reactions Requiring More than Two Half-Oscillations	
	RD	RCT	RD	RCT
4° in 4″	10	0	0	0
4° in 8″	65	30	45	0
4° in 16″	75	60	65	30
4° in 32″	80	70	60	65

point, some of the conditions favoring such waves will be indicated in our later discussion.

The distribution of the incidence of reaction within the first half-oscillation is given in Table 5, for 4 degrees in 4, 8, 16, and 32 seconds. Due to the fact that the distribution was similar in all four speeds of oscillation, the reactions at each point along the curve are pooled in Table 5 for all the speeds.

For reasons which we have already discussed each half-oscillation is regarded as a single stimulus for measuring compensation; a reaction occurring during any half oscillation is considered a response to that particular oscillation.

There is evidence in Table 5 of a marked variation in the point of incidence of compensatory response after the initiation of the rotation stimulus. Reactions may occur all the way from the beginning to the end of the first half-oscillation, with the majority of reactions occurring during the first half of the curve for both subjects—that is, during the positive acceleration period. Reaction may be delayed even beyond the first half-oscillation. Data from these same four speeds of oscillation at 4 degrees, showing the number of oscillations that is necessary to evoke a response, are given in Table 6.

At 4 degrees in 4 seconds only 10% of the reactions in the case of RD, and 0% in the case of RCT, require a second half-oscilla-

tion to evoke a response. At 4 degrees in 8 seconds 65% (RD) and 30% (RCT) of the reactions require more than one half-oscillation for their initiation, and 45% (RD) and 0% (RCT) require more than two. Our data are not complete on more than the first two half-oscillations. Our interpretation of this table is,

TABLE 7

Incidence of reactions in the entire special series of half oscillations, at 4° in 4" and 8". Units of half-oscillation curve given in mm.

Curve Units	Frequency of Reactions			
	RD		RCT	
mm.	4° in 4"	4° in 8"	4° in 4"	4° in 8"
0	4	6	1	2
1	8	8	1	5
2	6	6	5	4
3	10	2	2	5
4	8	4	5	8
5	15	1	8	7
6	12	2	7	3
7	7	2	4	1
8	9	2	5	2
9	5	2	10	3
10	7	2	12	1
11	1	1	4	4
12	3	2	4	4
13	2	1	4	0
14	0	1	4	0
15	2	3	4	3
16	0	1	2	2
17	0	2	3	0
18	0	2	0	2
19	0	6	4	6
20	1	2	6	3
Totals	106	58	95	65

that as the speed and intensity of oscillation decrease, the more is summation of stimuli necessary to evoke a response.

The incidence of reactions in a series of half-oscillations for 4 degrees in 4 and 8 seconds is given in Table 7 for both subjects. The variation manifest in these reactions to successive half-oscillations is closely similar to that found in reactions to the beginning oscillation. The series of records from which these data were taken were obtained under special conditions. The reaction was not the otherwise customary gradual compensation, but a quick movement of the recording lever to indicate as sharply as possible the moment of the perception of motion.

4. *Negative Compensatory Reactions*

Negative compensatory reactions which occur commonly at low frequencies and intensities of oscillation are phenomena worth some consideration. The negative response is not merely a reaction in the wrong direction; it involves perceiving the motion in the wrong direction as well. The frequency of nega-

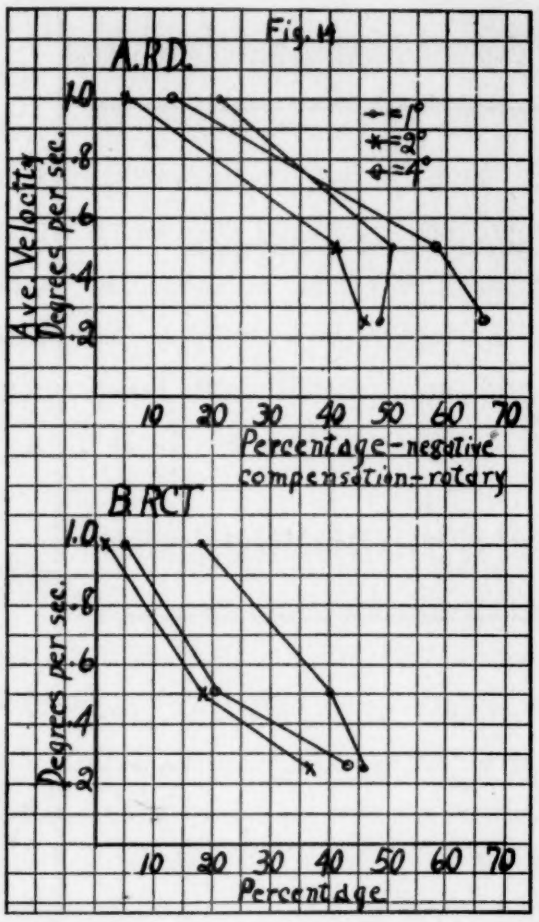

FIGURE 14. *A* and *B*, relation between the percentage of negative compensation and average velocity for three amplitudes of oscillation.

tive compensation is represented in Figure 14 for all three amplitudes of stimulation. The ordinate shows the average velocity in degrees per second; the abscissa, the percentage of negative compensations. The curves clearly indicate a decided increase of perception of motion in the wrong direction with a decrease in frequency and intensity of stimulation, especially in the case of RD. Various possible interpretations of negative reaction will be considered under the section on Interpretations and Theoretical Considerations, Chapter V.

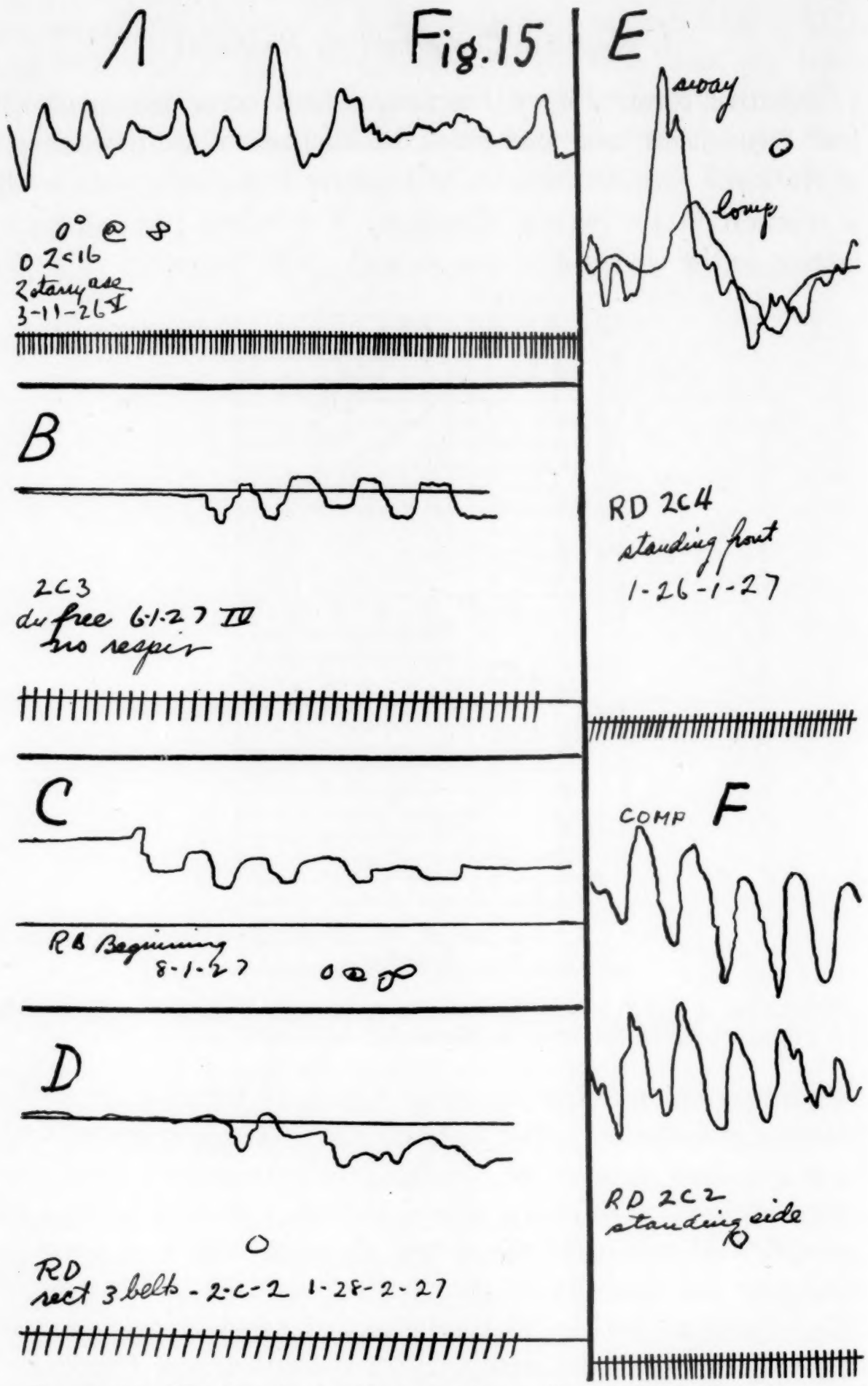

FIGURE 15.* RD. Records of subject's reactions to illusory oscillations during periods without physical displacement. *A*, record following rotary oscillation period of 2 degrees in 16 seconds. *B*, record following body-free rectilinear oscillation period of 2 cm. in 3 seconds. *C*, record at beginning of day's experiments in rectilinear oscillation, head-on-rest position. *D*, record following body-strapped rectilinear oscillation period of 2 cm. in 2 seconds. *E*, record following standing antero-posterior oscillation period of 2 cm. in 4 seconds,—the records of body sway and compensation are marked. *F*, record following standing lateral-rectilinear oscillation period of 2 cm. in 2 seconds.

* See footnote to Fig. 4.

5. *Perception of Motion Without Physical Displacement*

Not only was each series of oscillations arranged in an order unknown to the subject, but each series also included in unknown order two periods without physical movement. The idea of the *still-periods* was to discourage any possible oscillation "set" and to provide conditions for finer discrimination. In about 65 per cent of these periods there was clear consciousness of movement with consequent compensatory reaction, which differed in no distinguishable manner from the perception of motion evoked by physical oscillation. The phenomenon is of considerable importance to a theory of the integration of stimuli, though its psychophysiological explanation offers many difficulties.

Previous oscillation seemed to have little direct effect on the speed and amplitude of apparent oscillation during the still-periods. The frequency of the illusory oscillations, however, is commonly slower than that of the previous oscillatory period. Figures 15 and 16 reproduce records obtained in the still-periods of both rotary and rectilinear oscillation. The straight horizontal line represents the record of a motionless platform, the curved line represents the subject's reaction to the illusion.

In view of the fact that both subjects compensated for illusory oscillation even when the still-period occurred at the beginning of the day's experiments, the phenomenon cannot be identified with after-images. Even when the still-periods occurred after oscillation, the mechanical disturbances in the vestibule had ample time to gain their equilibrium long before the apparent motion in the still-period was recorded. C in Figure 15, A and E in Figure 16, represent the compensatory responses in the still-periods at the beginning of the day's experiments. The time line for C, Figure 15, is in B and serves for both.

E and F in Figures 15 and 16 are records of a standing subject during still-periods in rectilinear oscillation, compensation follows the body sway. This is congruent with the predominance of the kinaesthetic data under these conditions, as will be seen in the section on rectilinear oscillation. It is noteworthy that for all the bodily positions in both rotary and rectilinear oscillation,

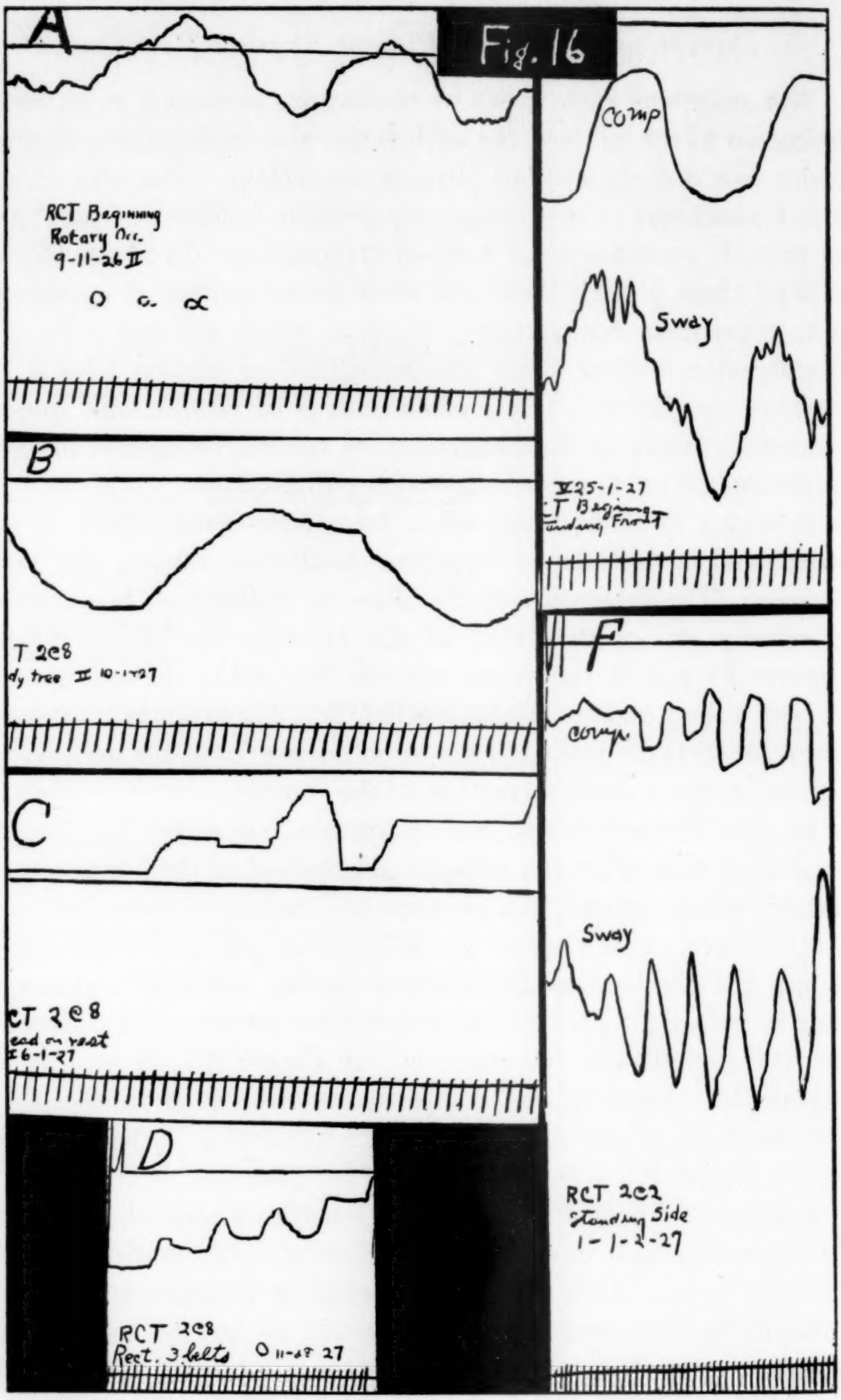

FIGURE 16.* RCT. Records of subject's reactions to illusory oscillations during periods without physical displacement. *A*, record at beginning of day's experiments in rotary oscillation with head-on-rest. *B*, record following body-free rectilinear oscillation period of 2 cm. in 8 seconds. *C*, record following head-on-rest rectilinear oscillation period of 2 cm. in 8 seconds. *D*, record following body-strapped rectilinear oscillation period of 2 cm. in 8 seconds. *E*, record at beginning of day's experiments in standing antero-posterior rectilinear oscillation. *F*, record following standing lateral-rectilinear oscillation period of 2 cm. in 2 seconds.

* See footnote to Fig. 4.

except in rotary oscillation with visual cues, compensatory responses are similar in both the still and oscillation periods.

An analogous phenomenon in rotary oscillation, where the platform is oscillated for ten complete oscillations and then stopped

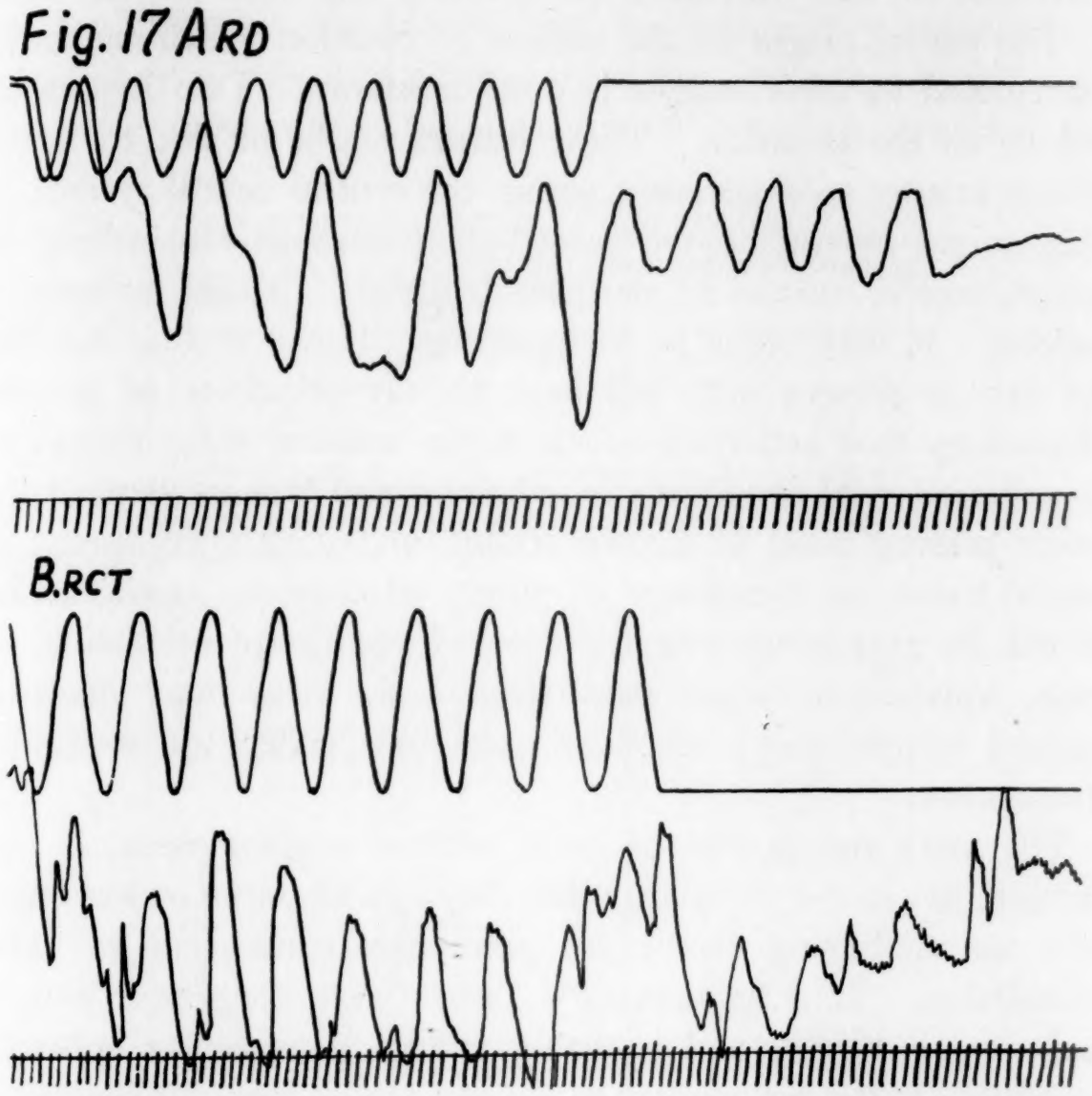

FIGURE 17.* *A*, RD, and *B*, RCT. Records of compensation during oscillation and after the oscillating platform was stopped. The oscillation period for *A* is 1 degree in 4 seconds, for *B* it is 2 degrees in 8 seconds.

without the knowledge of the subject, may be an after-image of oscillation. (See Figure 17.) The response continued after the platform was stopped, finally died out in the case of RD, and became very irregular in the case of RCT. Even in this case the phenomenon is probably the result of complication by central processes.

* See footnote to Fig. 4.

Since the pioneer observations of Külpe, confirmed by Perky (16) and others, the qualitative similarity or identity of the image and the percept from near threshold stimuli has come to be part of our psychological tradition. Recognition of the influence of this confusion on behavior has been less common.

The neural origin of the images of rotation which cannot be interpreted as after-images is quite unknown. Two hypotheses belong to the tradition. These images might be due to neural action arising spontaneously within the central neural system, or they might be due to the spread of fortuitous kinaesthetic or proprioceptive stimuli of peripheral origin. Crucial evidence is lacking. It may never be forthcoming. However that may be, we can at present only fall back on the principles of general physiology that action of neural tissue without some change in its external vital conditions is unknown and that in view of the never ceasing flood of known stimuli and its known spread in neural tissue the hypothesis of purely spontaneous neural action would be gratuitous. In the case of rectilinear oscillation, at least, kinaesthetic sense data from body sway may occasion manual compensatory reactions quite independent of vestibular stimulation.

The main significance of these subjective phenomena, in our opinion, lies in the probability that they operate more or less regularly as modifying factors in perception consequent to faint stimulation. If a hallucinatory factor were congruent with a real one, it might, and probably would, increase its apparent intensity. If it were opposed to the real factor, it might neutralize or reverse the latter according to its relative force. The psychology of perception and everyday experience is full of instances for which such summations and rivalries would offer an easy, perhaps too easy, explanation. They cannot be ignored as conditions of human variability in consciousness and reaction. Their importance has long been recognized in psychological experiments where the lack of knowledge of the objective sequence aims to protect the results from bias by reducing the subjective factor to its lowest terms, with a presumptive chance distribution of the irreducible minimum.

6. *The Relative Rôles of Non-vestibular Receptors in the Perception of Rotary Oscillation with the Subject at the Axis*

The rôle of audition in the perception of rotary oscillation was not studied in our experiments, but preliminary experiments indicated very little data arising from this sense field that would contribute to the perception of oscillation with such stimuli as we

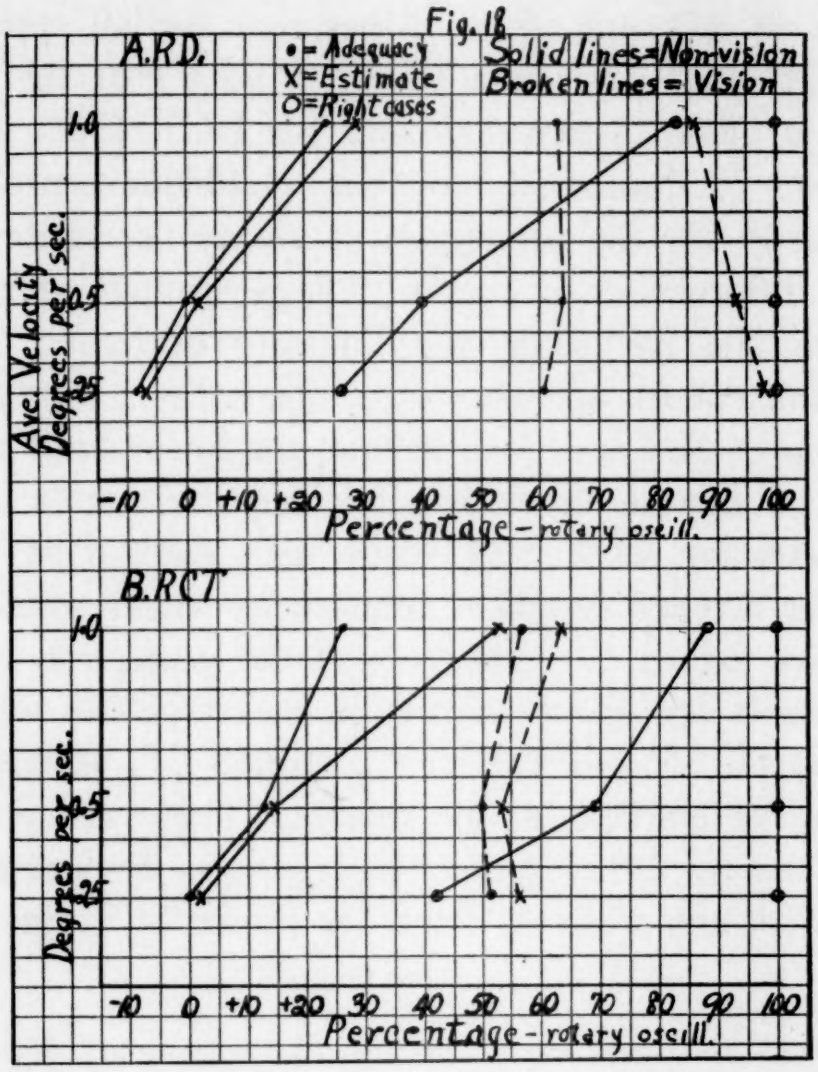

FIGURE 18. *A* and *B*, relations between the percentage of right responses, percentage of adequacy and percentage of estimate of motion with and without visual cues.

used. Nevertheless, we regularly masked all possible effects by constant noises which rotated with the subject.

The general knowledge that vision plays a relatively large part in the ordinary perception of rotation in our experiments is confirmed by the data reproduced in Figure 18.

A and B, Figure 18, show the difference between the non-visual and the visual situations for both subjects as to the percentage of right responses, the adequacy of response and estimate of perception of motion. Without a single exception, the subject compensated in the right direction for movement of the platform with the aid of vision. Furthermore, the adequacy of compensation and estimate of movement are high for the situation with vision. The adequacy ranges from 60 to 65 per cent for all speeds in the case of RD and 50 to 57 per cent for all speeds in the case of RCT. RD's estimate (86% to 95%) of the extent of movement is much higher than that for RCT (53% to 65%). When vision is eliminated, and the vestibular sense is relied upon primarily for the perception of rotary oscillation, we find an entirely different set of curves. The percentage of right cases decreases as the frequency and intensity decrease. The same relation holds true for adequacy of compensation. In other words, we have approached and gone beyond the lower limit of reliable perception of motion in these particular stimulation conditions for the vestibular sense field, while with the aid of vision we have not yet reached speeds or amplitudes which would produce a progressive decrease in adequacy of the perception of motion. There is much over-compensation in the responses with vision, especially at the 2- and 4-degree amplitudes. Individual differences are quite marked in this respect. There are no negative compensations for either subject with vision. Typical records of responses with and without vision are shown in Figure 4.

7. The Effect of Training Upon the Perception of Motion With and Without Visual Cues

The variation from day to day in terms of the adequacy of the compensation for rotary oscillation for ten days is shown in Figure 19. A and B represent the variation without vision, and C and D with vision. To conserve space, the curves for only the 2-degree amplitude are given. They are fairly typical of the others. Little or no improvement took place for either subject except with visual cues, and then only slight. Within the limits

of our data these curves show that the vestibular sensori-motor patterns are not subject to much improvement when vision is eliminated. They suggest relatively stable patterns of protopraxic adjustment.

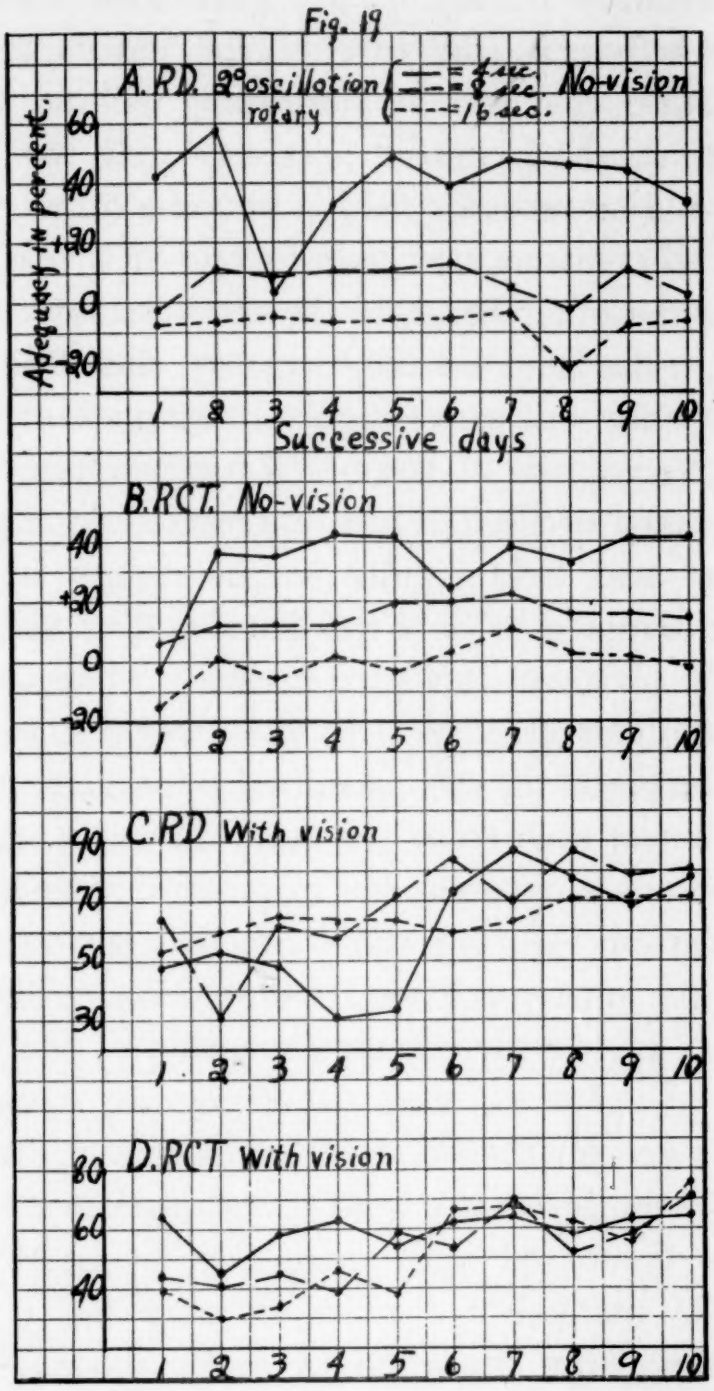

FIGURE 19. *A* and *B*, variation and the effect of practice on the adequacy of compensation for ten days without visual cues for 2 degrees oscillation in 4, 8 and 16 seconds. *C* and *D*, same as *A* and *B* except with visual cues.

8. *Voluntary Compensation by the Head for Rotary Oscillation*

The relative importance of vestibular receptors in perceiving oscillation near the threshold is a question that may be of some practical moment if thresholds are ever used clinically. There seemed to be only one way to eliminate vestibular cues during passive oscillation, that was by attempting to hold the head fixed in space while the body moved passively with the rotation platform. If the major receptor field is in some other portion of the body, then head compensation ought to prove a feasible means of response. On the other hand, if the semicircular canals or some other organs in the head are the receptors, then this type of compensatory response will prove highly inadequate or impossible.

The objective records of attempted compensatory responses of the head to rotary oscillation are represented in Figure 20. The response lever was held rigidly in the mouth of the subject. The subject attempted to hold the distal end of this lever still in space while the platform oscillated his body. The smooth, regular curves are the platform record; the irregular curves are the responses. The platform was permitted to oscillate only two complete oscillations at each trial. In every alternate trial the subject was instructed not to respond, but to practice attending to various cues to oscillation. During these practice periods there is apparently a slight but regular negative reaction. This is an instrumental artifact due to the eccentric position of the head in front of the axis of rotation, thus producing an excursion of the response lever greater than that of the platform lever.

Throughout the series the head compensation is very irregular and jerky as compared with manual compensation. However inadequate the manual compensation may be, it is relatively smooth, seldom being corrected by jerky movements after the onset. The jerky, irregular compensation curves of the head indicate that when the motion is perceived, the head compensates rapidly, and then stops in order to sense the motion again. In other words, the compensation interrupts the perception of motion. This statement is confirmed by the introspections. The subject will perceive the motion and respond, but during the response he

has lost the direction and extent of the motion. This experiment on intact vestibular receptors extends the data from ablation experiments on animals. Not only is the specific receptor for rotation vestibular, but in oscillation near the threshold vestibular

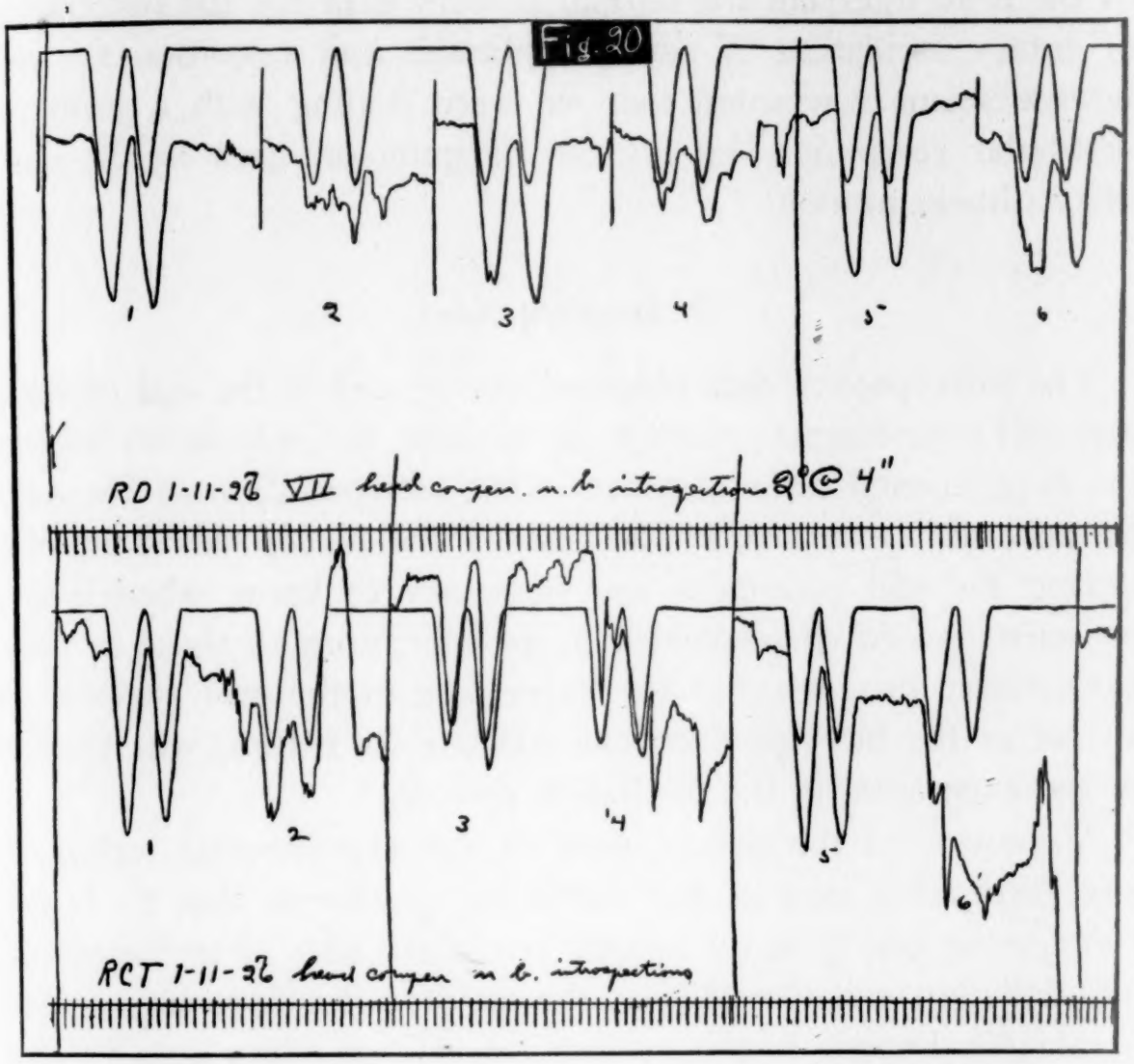

FIGURE 20.* Records of head-compensation. The first, third and fifth pairs of oscillations were not compensated for. The second, fourth and sixth pairs were compensated for by head movements.

data are the only ones that are adequate without visual and kinaesthetic cues.

The question arises as to the fate of those vestibular stimulations that arise during the voluntary compensatory head movements. They should be of the same order as the passive movements which are stimuli to compensation, yet so far as we can interpret our results there is no extra compensation consequent

* See footnote to Fig. 4.

to the vestibular disturbances of antecedent head compensation. In some way or other active movement inhibited the development of a response.

The main point of the experiment is clear. Since movements of the head interrupt the normal sensory data for the perception of rotary oscillation of small amplitudes and velocities, the inference seems warranted that we were dealing with a primary vestibular receptor. The evidence is quite different in the case of rectilinear motion.

9. *Introspections*

The introspective data obtained during and at the end of each series of experiments proved to be valuable, not only in developing the experimental technique, but in the interpretation of the data as well. For example, in the case of the perception of motion during the still periods it was necessary to know whether the objective record corresponded in its indications to those of consciousness; also, whether the experience in the still periods, in so far as the introspections can indicate its nature, was similar to the experience in the oscillation periods.

Moreover, in the development of the experimental technique any perceptible jars in the oscillating platforms due to faulty functioning may give the subject secondary cues as to the period of oscillation and thus distort the results. Introspection served a valuable purpose in this connection. If secondary cues of this sort developed at any time, the experiment was discontinued until they had been eliminated.

The introspective data will not be otherwise reported due to their excessive demands on space and the fact that they are as a whole less reliable than the objective records with which they roughly correspond.

B. Passive Rectilinear Oscillation

The amplitudes, frequencies, average velocities, and average accelerations of the rectilinear oscillation used in our experiments are given in the following table:

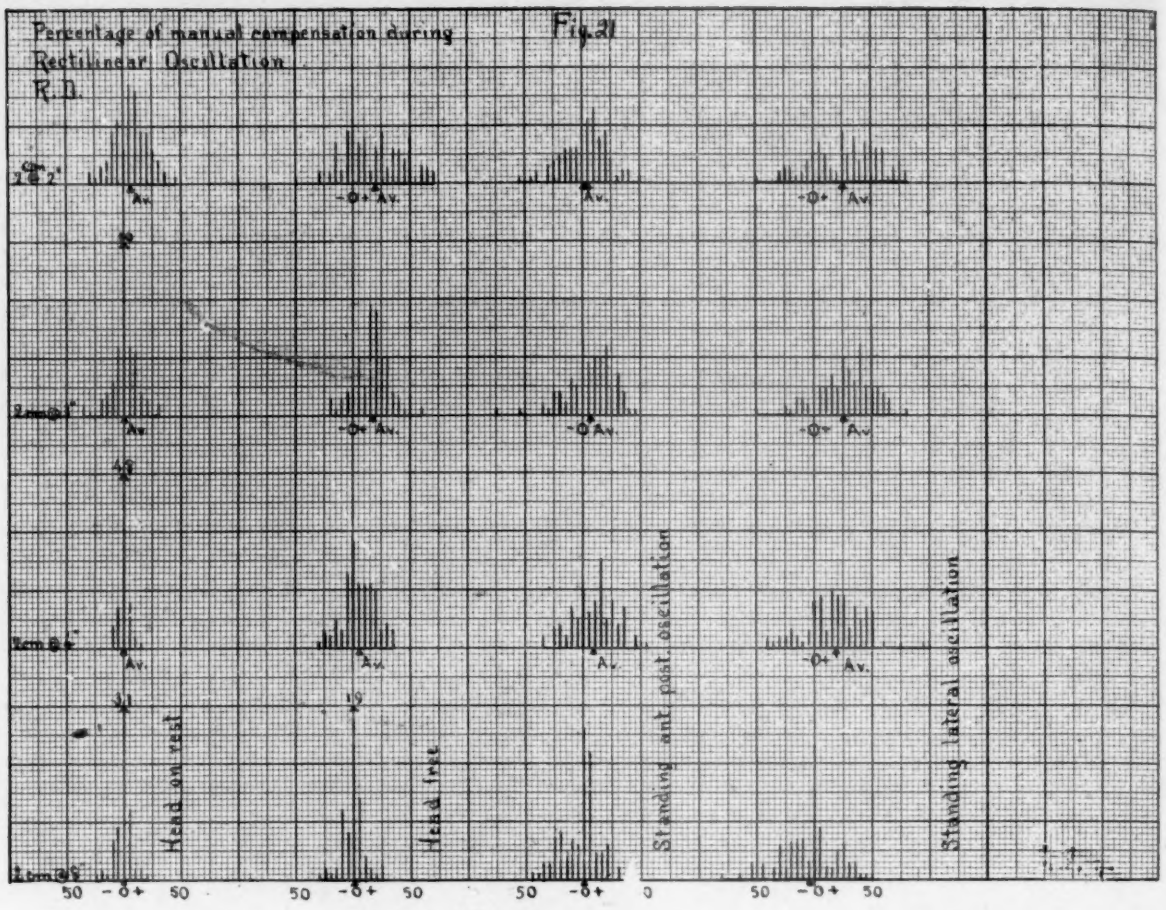

FIGURE 21. RD. Distributions of percentages of manual compensation for rectilinear oscillation for the sitting head-on-rest, sitting body-free, standing while oscillating in the antero-posterior plane and in the lateral plane.

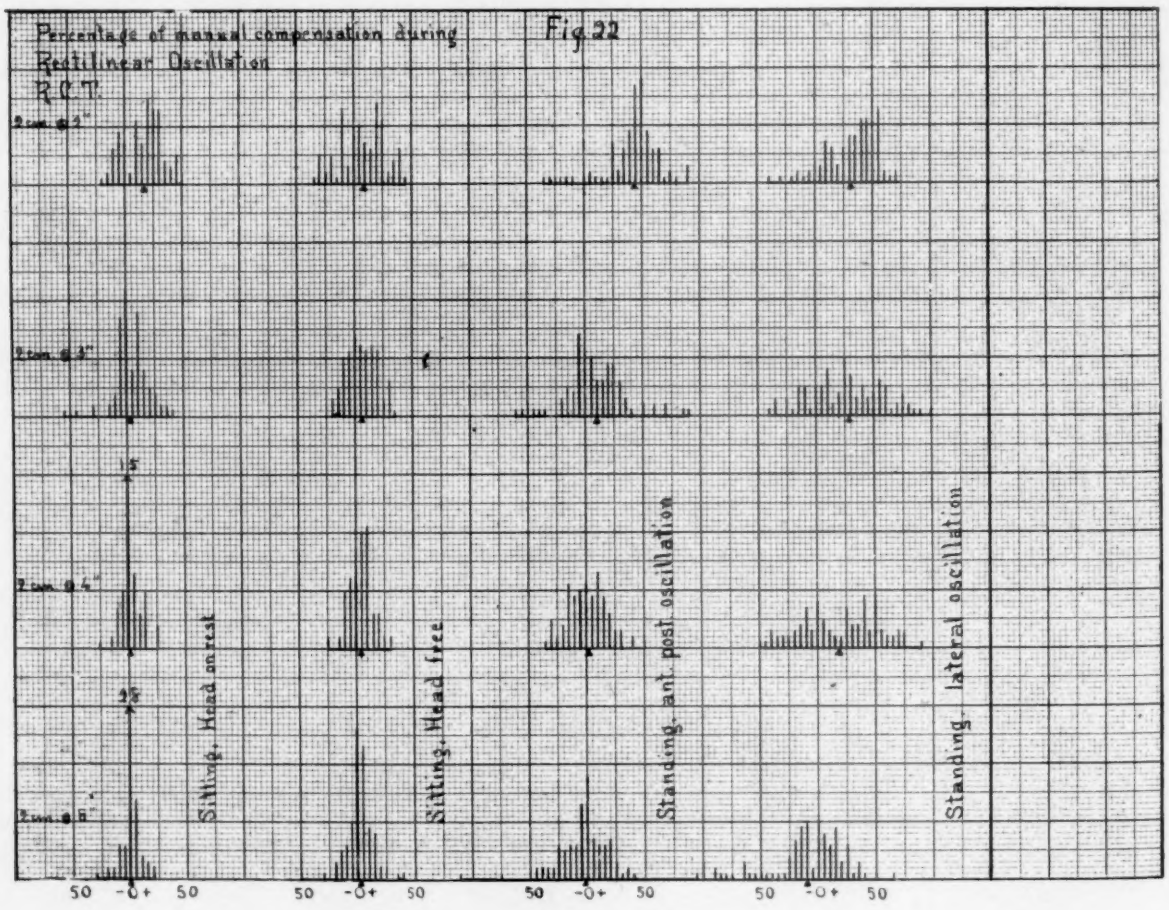

FIGURE 22. RCT. Distributions of percentages of manual compensation for rectilinear oscillation for the sitting head-on-rest, sitting body-free, standing while oscillating in the antero-posterior plane and in the lateral plane.

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Oscillation Amplitude CM.	Oscillation Period Sec.	Average Velocity CM. per Second	Average Acceleration CM. per Second
4	2	2	24.8
4	3	1.33	11
4	4	1	6.2
4	8	0.5	0.4

1. *Distributions of Compensations*

The distributions of the percentages of right responses in voluntary, manual compensation for rectilinear oscillation for the sitting head-on-rest, sitting body free, standing while oscillating in the antero-posterior plane and in the lateral plane are given in Figures 21 and 22 for RD and RCT. The distributions for the sitting position with head and body strapped to the chair are not given; they are similar to those of the sitting head-on-rest position.

The orderly relationship between stimulus and percentage of right responses far below the supposititious threshold, together with the inclusion of negative compensations in the same normal distribution with positive compensation, leads one to the same doubts respecting the exclusive use of the concept of the limen that we expressed in regard to rotary oscillation. Some of the conditions that make for negative compensation are, however, much clearer in this case and suggest a more complicated integration of sensori-motor impulses than we have hitherto considered.

The arithmetic mean or average is indicated in each distribution by an arrowhead. It is clear that as the acceleration and frequency of oscillation decrease the percentage of positive compensation decreases for each bodily position. The two sitting positions are the least variable for both subjects with respect to the relative amounts of negative and positive reactions. The standing positions manifest greater variation in compensatory reaction, but the variability is less than that found in response to rotary oscillation of small amplitude.

2. *Relations Between the Percentage of Right Responses, the Average Velocity, Average Acceleration and Frequency of Stimulation*

Figure 23, A and B, give the relation between the average velocity and the percentage of right responses for the five different bodily positions in rectilinear oscillation. All the curves have the same general slope in the case of RCT. More variation is manifest in the case of RD. In the sitting body-free and standing positions for RD the greatest number of right responses fall

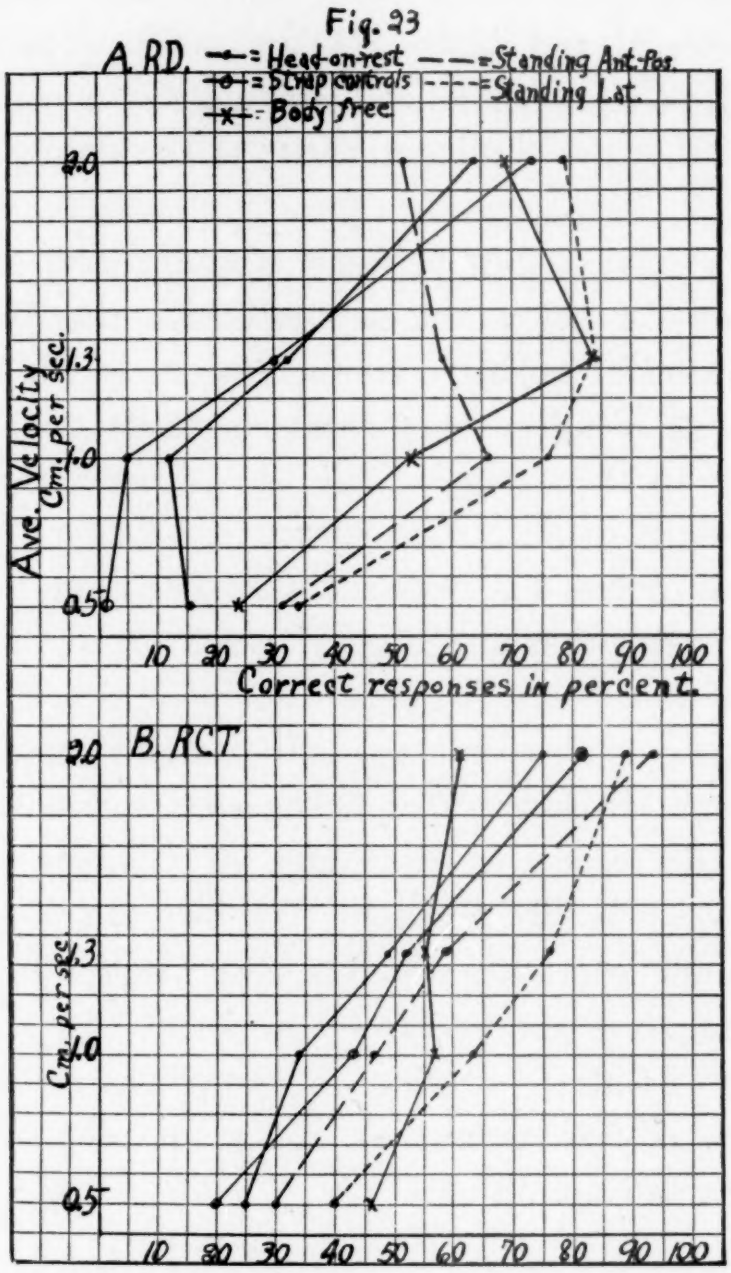

FIGURE 23. *A* and *B*, relation between the average velocity and percentage of right responses for the five different bodily positions in rectilinear oscillation.

at 1 and 1.33 cm. per second; while in the sitting head-on-rest and sitting with the body strapped to the chair show that a decrease in average velocity and frequency produces a decrease in the percentage of right responses.

Table 8 gives the average velocity and average acceleration in cm. per second corresponding to 50% right responses for the five different bodily positions for both subjects.

TABLE 8

Rectilinear oscillation stimuli corresponding to 50% right responses for the different bodily positions, in cm. per second.

	Average Velocity		Average Acceleration	
	RD	RCT	RD	RCT
Sitting, body-strapped	1.6	1.3	17	9
Sitting, head-on-rest	1.7	1.4	19	12
Sitting, body-free	.9	.7	6	3
Standing, ant-pos. oscillation	.8	1.1	4	7
Standing, lateral oscillation	.7	.7	3	3

Analogous results from both subjects indicate that some factor is present when the body is free to move that produces a more adequate perception of rectilinear oscillation than when the body is supported by rests. In the case of RD the standing positions result in greater sensitivity than the sitting positions, but the differences between standing and sitting body-free positions are too small to be significant. We interpret these results to mean that kinaesthetic data are more important in rectilinear oscillation than data of vestibular origin. On the whole, it makes little difference whether the body movement occurs with the hips as an axis or with the ankles.

In order to obtain the relationship between the frequency of stimulation and the adequacy of response with the average velocity constant, we conducted another series of experiments in which the stimulus combinations were 4 cm. in 2 sec., 8 cm. in 4 sec., and 12cm. in 6 sec. The average velocity remained constant at 2 cm. per second, while the frequencies varied as 2, 4, and 6 seconds.

The relation between the percentage of right responses, the percentage of adequacy, and the frequency of stimulation with

the average velocity constant at 2 cm. per second in the sitting head-on-rest position is shown in Figure 24, for both subjects.

As the frequency decreases from one-half oscillation in 1 second to one-half in 3 seconds, the percentage of right responses decreases from 84–87 to 33–54 per cent; while the percentage

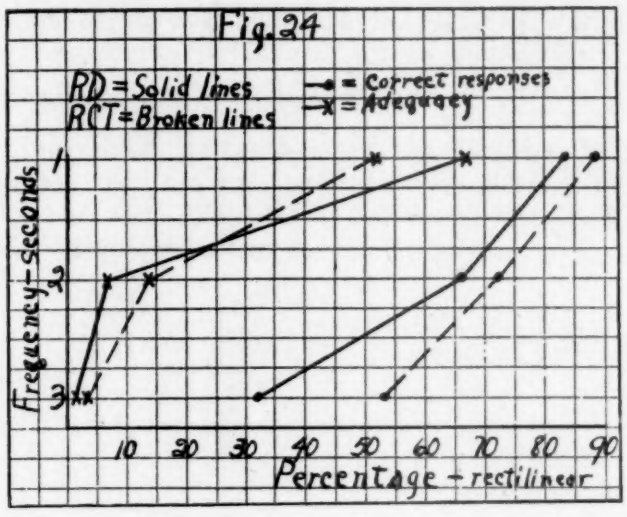

FIGURE 24. Relations between the percentage of right responses, percentage of adequacy and frequency of stimulation with average velocity constant at 2 cm. per second.

of adequacy decreases from 52–67 to 3 per cent for both subjects, notwithstanding the fact that the average acceleration increases from 25 cm. per second at 4 cm. in 2 seconds to 50 cm. per second at 8 cm. in 4 seconds and to 75 cm. per second at 12 cm. in 6 seconds. The frequency of stimulation seems to be more important in producing adequate excitation in rectilinear than in rotary oscillation. These results contrast sharply with those in rotary oscillation and seem to indicate different receptors and a different mechanics of receptor stimulation.

Velocity also seems to be a basic factor in the stimulus of rectilinear oscillation as indicated in Figure 25. As the average velocity decreases from 3.5 to 0.25 cm. per second, with the constant frequency of 2 seconds between stimuli, the percentage of right responses decreases from 64–77 to 20–25 for both subjects. A decrease of average velocity from 2 to 0.5 cm. per second results in a decrease in percentage of right responses from 64–75 to 43–29 for RD and RCT respectively.

3. *Analysis of Body Sway in Rectilinear Oscillation of a Standing Subject*

An analysis of the objective records of body sway in standing on the platform during rectilinear oscillation reveals three changes in the station of the body as given in Figure 26. The axis of the body remains normal to the direction of movement only a very small part of the time during oscillation. Even when the platform

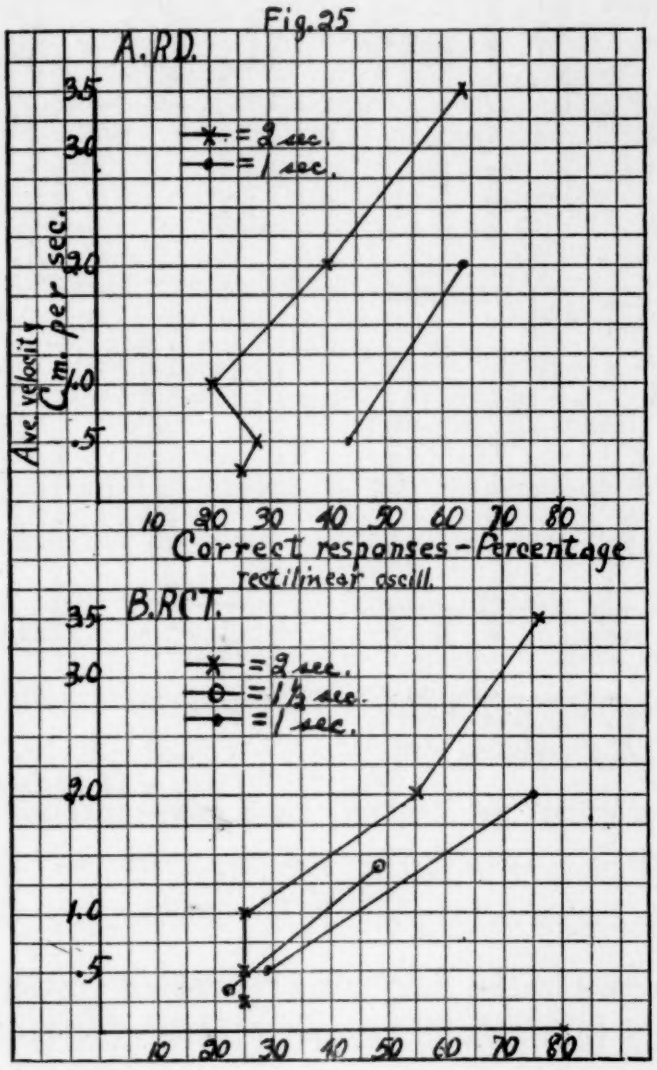

FIGURE 25. *A* and *B*, relation between the percentage of correct responses and the average velocity for 1 and 2 seconds frequencies in case of RD and 1, 1.5 and 2 seconds frequencies in case of RCT.

is quiet, the body axis is vertical only momentarily. Position *a* in all these diagrams represents the axis of the body when it is perpendicular to the platform. Position *b* I, shows the body axis just after the onset of the oscillation. The center of gravity of the body lags behind the movement of the platform for a fraction of a second due to its inertia. A sudden involuntary adjustment

by the skeletal muscles corrects the lag, *b* II, and moves the body farther in the same direction as the platform, thus producing a reflex bodily over-compensation, *b* III. This sequence of bodily positions occurs in about 90 per cent of the oscillations of the platform in which the body is free to move.

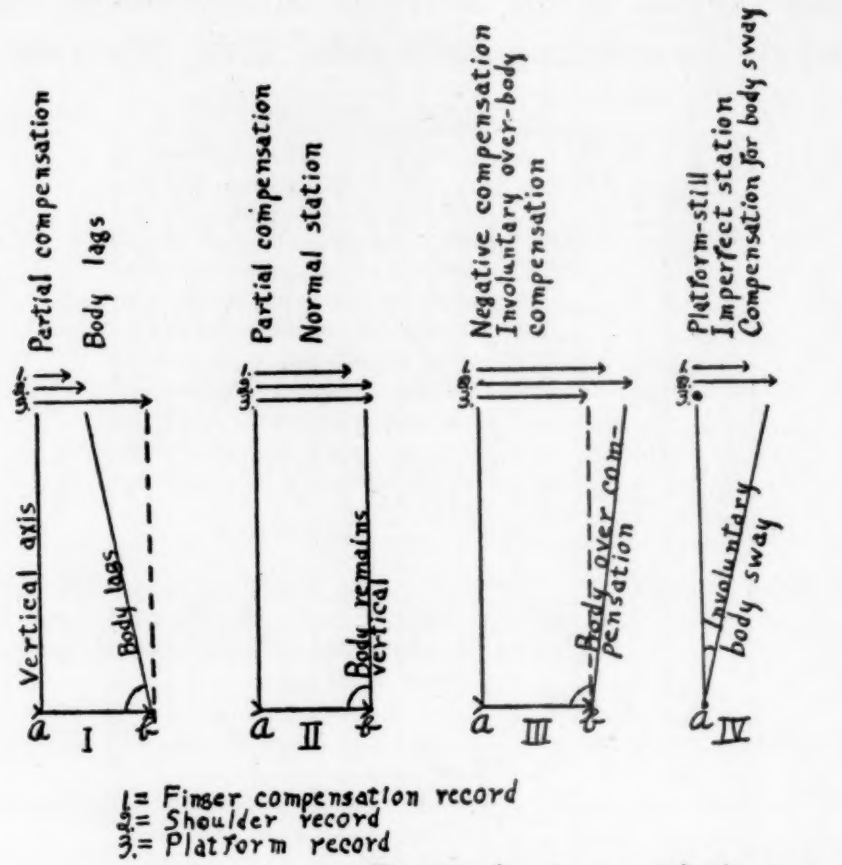

Fig. 26. Analysis of body sway and compensation.

FIGURE 26

The three arrows in the diagrams represent respectively the platform record, the body sway record (lever attached to shoulder), and the finger compensatory response. The arrows indicating finger compensation represent the majority of the manual compensatory responses to each particular bodily position.

Positions I and II in Figure 26 occur about 40 per cent of the time during each series of half-oscillations. Position III occurs about 60 per cent of the time during each series of half-oscillations.

The voluntary manual compensatory response in the standing position often occurs in the same direction as the body sway. The average correlation coefficient is .51 as given in Table 9.

Where the manual compensatory response is determined by body sway, and is in the same direction as the movement of the platform, the compensation to movement of the platform is consequently negative.

Position IV, Figure 26, represents the involuntary body sway during the still-periods. The subject responds manually to this

TABLE 9

Correlation between manual compensation and body sway in lateral and antero-posterior oscillation.

	RD				RCT				
	Standing Front		Standing Sideways		Standing Front		Standing Sideways		
Speeds	r	PE	r	PE	r	PE	r	PE	Ave.
2 cm. 2″.....	.27	.044	.48	.036	.51	.038	.20	.046	.37
2 cm. 3″.....	.38	.041	.69	.025	.43	.037	.72	.023	.55
2 cm. 4″.....	.42	.04	.64	.028	.68	.026	.63	.028	.59
2 cm. 8″.....	.43	.042	.53	.035	.55	.034	.56	.032	.52

Pooled average: .51 ±.036

involuntary body sway in about 80 per cent of the still-periods as if the platform were moving. More or less involuntary body sway occurs in every still period, but some of the sways are apparently too faint to be perceived. (See E and F in Figures 15 and 16 for the objective records.) Introspective analysis of these responses revealed the fact that when the body swayed the resulting kinaesthetic data were interpreted as though the platform moved the feet in an opposite direction. This undoubtedly accounts for a large number of the negative reactions in standing positions.

Our analysis seems to indicate a preliminary reflex or protopraxic bodily compensation for changes in bodily station whether of experimental or other origin, followed by conscious or manual compensation which may be conditioned by the original kinaesthetic stimulation evoking the reflex or by subsequent kinaesthetic stimuli caused by the reflex adjustment.

Table 9 gives the correlation coefficients by the Pearson product-moment method for manual compensation and body sway in both lateral and antero-posterior oscillation. The coefficients vary from .2 to .7 with a pooled average of .51±.036. The average

for each speed and amplitude for both subjects is given in the column to the right.

A frequency of two seconds seems to be more rapid than the normal body sway period, thus resulting in confusion between the body sway and platform oscillation. Furthermore, vestibular data are more nearly adequate at a frequency of two seconds.

TABLE 10

RD. Scatter diagram of the relationship between manual compensation and lateral body sway. 2 cm at 4". The abscissa represents body sway in mm. The ordinate represents compensation in mm.

Neg. Compensation	16	12	8	4	0	4	8	12	16	20	24
8.....						1		4			
4.....					1	3	5	2	3		1
0.....				1	6	6	16	5	2	2	
4.....				3	15	18	6	2			
8.....				6	30	11	6	3			
12.....			2	9	11	4	1	1			
16.....	1	2	1	1	2						
20.....		1									
	16	12	8	4	0	4	8	12	16	20	24

Compensation. Body sway in reverse direction, with oscillation

$r = .64 \pm .028$

These facts account, in part at least, for the low average correlation between body sway and manual compensation for this frequency. In other speeds of oscillation, where the oscillation period corresponds more closely to the normal body sway period, the responses are made more regularly to the kinaesthetic data arising from the body sway.

Tables 10–13, inclusive, represent correlation tables for each standing position for each subject at a frequency of four seconds. Since these tables are typical, to conserve space the other tables will not be given. On the whole these correlations indicate that kinaesthetic data are important factors in the perception of motion in the free standing positions.

Fourteen per cent of the body sway in the case of RD and 31 per cent in the case of RCT, produced an angular displacement which was probably above the threshold of the semicircular

canals. The figures in Table 14 represent the percentages of the total number of oscillations which produced body sway involving an angular displacement of the head above the angular velocity which evoked 50 per cent right responses in horizontal rotary

TABLE 11

RD. Relationship of manual compensation to antero-posterior body sway. The abscissa represents body sway in mm. The ordinate represents compensation in mm.

Compensation. Neg. Compensation	8	4	0	4	8	12	16	20	24	28	32
8.....						2			1		
4.....					4	7	2	2			
0.....			6	17	11	13	8	3	3		1
4.....	1		10	17	11	15	3				
8.....	1	3	12	11	7	7	2	2			
12.....			3	1	2						
16.....				1	1						
	8	4	0	4	8	12	16	20	24	28	32

Body sway in reverse direction, with oscillation $r = .42 \pm .04$

oscillation; *i.e.*, 0.6 degree per second for RD and 0.4 degrees per second for RCT.

If the vertical canals are approximately as sensitive to oscillation as the horizontal, they, as well as the kinaesthetic senses and the receptor for sensing rectilinear oscillation, are excited about one-fourth of the time during oscillation. The correlation between the extent of body sway of sufficient intensity to excite the semicircular canals and the extent of manual compensation is represented by the Pearson product-moment coefficient of $.64 \pm .019$ for RD and $.60 \pm .014$ for RCT. The correlation coefficient obtained when the body sway is below the 50 per cent threshold of the canals, when correlated with the extent of manual compensation, is $.44 \pm .018$ in the case of RD and $.31 \pm .27$ in the case of RCT.

The relatively high correlation between body sway which is sufficient to evoke 50 per cent right responses to rotary oscillation and the manual compensation, and the lower correlation between

the body sway below that point and manual compensation show, in the one case, that the compensatory responses are determined predominantly by kinaesthetic data and, in the other, that the two sets of data conflict, with slight predominance of the rectilinear vestibular data. The higher coefficients indicate that the kinaesthetic cues predominate, notwithstanding the fact that the body sway is of sufficient intensity to excite the semicircular canals. Thus, the vestibular data aroused by the body sway, the vestibular

TABLE 12

RCT. Relationship of manual compensation to lateral body sway. 2 cm. at 4". The abscissa represents body sway in mm. The ordinate represents compensation in mm.

Neg. Compensation	16	12	8	4	0	4	8	12	16	20	24	28	32	36	40	44
16...												1				
12...							1									1
8...			1				1	3			1	2	1	1		1
4...							2	2	1	4	1	3	2	2	1	4
0...			1	2			4	2	5	4	4	4	2	3		1
4...		3	1	1	5	2	3	4	2	5	3	1	1			
8...	3	2		1	2	2	5	4	5	3	2		1			
12...	2	1	5	1	6	8	6	4	3	1						
16...	2		3	1	6	2	2						1			
20...	1	2			2	2										
	16	12	8	4	0	4	8	12	16	20	24	28	32	36	40	44

Pos. Compensation.

Body sway in reverse direction, with oscillation $r = .63 \pm .028$

data aroused by rectilinear motion of the platform and the kinaesthetic data are frequently in evident rivalry or conflict. And when the sway becomes of sufficient extent and acceleration, the response is made to the kinaesthetic cues with an apparent inhibition of the rectilinear-rotary vestibular data; with a less amount of sway the response is made to the rectilinear vestibular data.

The conflict between the various kinds of receptor data and the reactions they evoke seems to be a promising lead in analyzing the psycho-physiological consequences of moving platforms. In the function of maintaining bodily equilibrium on a moving plat-

form one might expect these three sense fields to participate equally in furnishing data as to the changes in bodily position in swaying, but it appears that this is not the case, as indicated by our data. They probably constitute a kind of sensory reinforcing system, by means of which in extreme instances of sway the less sensitive participants reinforce or modify the reaction evoked by more sensitive receptors. The mechanism seems to be adapted to maintaining an upright position rather than the perception of

TABLE 13

RCT. Relationship of manual compensation to antero-posterior body sway. 2 cm. at 4″. The abscissa represents body sway in mm. The ordinate represents compensation in mm.

Neg. Compensation.	12	8	4	0	4	8	12	16	20	24	28	32
12.....										2		1
8.....					1		3	4	4			
4.....					4	4	8	6	7	2		1
0.....			2	6	4	9	16	7	2	2		1
4.....		2	2	6	15	22	7	5	2	1		
8.....		1	5	13	4	2	2	1				
12.....	1	1	3	4	1							
16.....		1	1	1								
	12	8	4	0	4	8	12	16	20	24	28	32

Body sway in reverse direction, with oscillation $r = .68 \pm .026$

motion of a supporting base. In the former case the data reinforce each other; in the latter they are in rivalry. This may be one of the factors in the production of seasickness.

In view of the fact that there are probably three different sense fields interacting in the perception of oscillatory motion in the standing positions, the kinaesthetic, the rotary-vestibular, and the rectilinear-vestibular, it seemed desirable, not only to fractionate the vestibular data into the rotary and rectilinear components, but also to isolate experimentally the kinaesthetic data.

To this end the experimental arrangement was somewhat altered. The subject's shoulders were held rigidly by a special offset which was held stationary in space while the platform

moved. This was accomplished by a strap tightly fastened around the chest, encompassing the arms, and fastened to the projections of the special offset in front and behind the subject. This arrangement permitted the platform to oscillate the subject's feet under him with the shoulders as the pivot. Furthermore, due to the pressure of the strap around the chest, the cutaneous receptors of that area furnished no clear cues to oscillation. Introspectively

TABLE 14

Percentage of total number of oscillations in which body sway produced sufficient speed and angular displacement of the head to excite the semicircular canals sufficiently to evoke 50 per cent right reactions.

	RD			RCT		
Stimulus	Lateral	Ant.-Pos.	Ave.	Lateral	Ant.-Pos.	Ave.
2 cm.—2″	22	23	22	35	33	34
2 cm.—3″	12	23	18	38	31	34
2 cm.—4″	6	18	12	38	31	34
2 cm.—8″	2	7	4	27	18	22
			Ave. 14			Ave. 31

the cues of motion came from the feet, ankles, and lower limbs. The subject stood fairly relaxed, so that smooth oscillation of the platform was not interfered with. The subject's eyes were covered, the masking noise produced, and the same means of response used. In view of the fact that all the speeds and amplitudes of oscillation previously used were clearly perceived under these experimental conditions of passive oscillation, the amplitude was reduced to 0.5 cm., with frequencies of 2, 4, 8, and 16 seconds. Judged by the percentage of right responses, one oscillation in 16 seconds at this amplitude was as clearly perceived in case of RCT, and almost as clearly perceived in the case of RD, as one oscillation in 2 seconds. In other words, we failed to reach the lower limit of adequate compensation to kinaesthetic stimulation, even with an average velocity of .062 cm. per second, and frequency of 1 oscillation in 16 seconds, about one-fourth the intensity at which compensation to oscillation otherwise almost disappeared.

It seems clear, if one can generalize our experimental findings on this point, that kinaesthesis yields an entirely different sensory datum as compared with that provided by the vestibular mech-

anism and that the pure kinaesthetic threshold for body sway is far below any threshold thus far obtained for passive oscillation in the standing and sitting positions in rectilinear directions of oscillation. The sensitivity of the normal kinaesthetic receptors is comparable only to that of vision in the perception of body sway. These results confirm the findings of Miles,* and should have important bearings on tests for aviators.

4. *Positive and Negative Compensations to Successive Half-Oscillations for the Sitting Head-on-Rest Position*

In analyzing the moments at which reactions take place after the initiation of the stimulus, with stimuli of 4 cm. in 2 seconds, 8 cm. in 4 seconds, and 12 cm. in 6 seconds, it is clear from Table 15 that as the frequency of stimulation decreases with

TABLE 15

Percentage of positive and negative reactions occurring on acceleration and deceleration periods of oscillation at changing frequencies with constant average velocity.

Stimulus	Percentage of Positive Reactions Occurring on Acceleration Phase		Percentage of Negative Reactions Occurring on Deceleration Phase	
	RD	RCT	RD	RCT
4 cm.—2″.....	84	95	50	56
8 cm.—4″.....	76	86	64	71
12 cm.—6″.....	72	77	69	69

average velocity constant, the percentage of positive reactions occurring on the acceleration period decreases; while the percentage of negative reactions on the deceleration period increases for both subjects. With stimuli of 4 cm. in 2 seconds the percentage of total negative reactions occurring on the deceleration period is about equal to that occurring on the acceleration period. There is a fairly equal distribution of negative reactions all along each half-oscillation in the case of 4 cm. in 2 seconds, as is indicated in Table 16.

As the frequency of stimulation decreased from one half-oscillation in one second to one-half in three seconds, the percentage of negative reactions occurring in the deceleration period increased from 50–56 per cent to 69 per cent for both subjects,

* *Op. cit.*

and the percentage of positive reactions occurring on acceleration period decreased from 84–95 to 72–77 per cent for both subjects. This indicates that as the frequency of stimulation decreases the deceleration period of the oscillation is responded to somewhat more consistently than the acceleration period; and, as the frequency increases with the average velocity constant, the acceleration period is responded to more consistently.

TABLE 16

Variation in moments of reactions to successive half-oscillations. Units of half-oscillation curve given in millimeters.

	4 CM. in 2″ Frequency of Reactions				8 CM. in 4″ Frequency of Reactions				12 CM. in 6″ Frequency of Reactions			
	RD		RCT		RD		RCT		RD		RCT	
Curve MM.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
0	36	1	53	2	18	2	28	3	8	2	10	2
1	15	1	44	4	7	1	7	0	2	2	8	1
2	19	1	18	3	6	2	7	1	5	3	6	1
3	14	4	17	2	7	2	10	2	6	3	6	2
4	7	0	14	3	3	2	5	1	3	1	3	2
5	15	0	6	2	1	5	5	2	5	1	2	2
6	10	2	6	3	4	0	2	1	1	0	2	3
7	11	1	4	2	5	2	4	0	1	0	2	3
8	5	0	5	2	5	0	3	1	1	2	0	1
9	7	1	3	0	4	2	3	2	3	3	1	1
10	12	2	2	4	1	1	2	1	0	2	2	0
11	6	0	2	2	4	1	2	4	1	2	4	2
12	6	1	0	2	2	3	2	1	1	2	1	3
13	3	0	0	0	2	1	2	3	0	6	2	3
14	1	0	0	1	3	2	2	1	1	4	0	9
15	3	1	2	5	1	3	1	0	0	2	0	2
16	0	1	1	4	4	6	0	6	1	5	2	7
17	1	2	1	4	0	2	1	6	0	3	3	5
18	3	2	2	4	3	4	1	7	2	8	5	7
19	3	2	1	3	1	5	1	5	3	7	0	5
20	2	3	1	9	2	5	2	8	5	3	0	6
					2	5	1	7	1	3	0	4

The variation in the time of the reactions after the beginning of the stimulus is significant. In all three stimulation-combinations—namely, 4 cm. in 2″, 8 cm. in 4″, and 12 cm. in 6″, the reactions spread over the entire range from the initiation to the cessation of the stimulus. This is true for both positive and negative reactions. The majority of the positive reactions, however, fall on the acceleration period; while the majority of the negative reactions, excepting for the 4 cm. in 2″, fall on the deceleration period. The distributions of the positive and negative reactions relative to their occurrence after the beginning of the stimulus in terms of millimeters on the platform curve are given in Table 16.

5. *Comparison of Sensitivity to Rotary and Rectilinear Oscillation*

There is in the tradition no direct measure for comparing the relative sensitivity of the vestibular sense organs for rotary and rectilinear oscillation. Frequency is comparable in both kinds of stimulation, but degrees of rotary oscillation are quite incomparable with centimeters of rectilinear displacement except in terms of the actual movement of the bony labyrinth. This seems to be the only common factor for a comparison of sensitivity.

In rotary oscillation with the subject at the axis, if the head is so placed that the axis of rotation runs midway between the right and left bony labyrinths, each labyrinth will be about 3 cms. from the axis of rotation. Assuming this to be the case, the actual movement of the bony labyrinth in one-degree rotation will be 0.053 cm. Fifty per cent right responses to rotary sine-wave oscillation is evoked by an average velocity of 0.5 degree per second in the case of RD and 0.3 degree per second in the case of RCT. The corresponding rectilinear values when the head is against a rest and the results least disturbed by kinaesthetic factors are 1.6 cm. per second for RD and 1.3 cm. per second for RCT. Thus, in the case of RD, the sensitivity for rotary oscillation is, $\frac{1.6}{0.5 \times .053}$, or 60 times greater than the sensitivity for rectilinear oscillation, in terms of the average velocity of the bony labyrinth in the two situations; in the case of RCT it is $\frac{1.3}{0.3 \times .053}$, or 81 times greater.

The difference appears still greater in terms of average acceleration. The average acceleration of RD's vestibule, corresponding to 50 per cent of right responses, is 0.0444 cm. per second in rotary and 17 cm. per sec. in rectilinear oscillation. Consequently, the ratio between RD's rotary and rectilinear sensitivity in terms of acceleration will be $\frac{17}{.0444}$ or 382 to 1. The corresponding values in the case of RCT are .0108 cm. per sec., and 9 cm. per sec., giving a relationship of 833 to 1 as the ratio of sensitivity.

Either of two hypotheses may account for these differences in vestibular sensitivity; the rotary and rectilinear motion may affect two different vestibular receptors, probably the semicircular canals and the utricle, or the semicircular canals may have different modes of irritability.

This comparison between the sensitivity of the vestibular receptors in terms of the movement of the bony labyrinth may appear somewhat artificial and gratuitous. As a matter of fact, only in the rarest instances does the axis of rotation lie midway between the horizontal canals. In the great majority of instances in actual life rotation is involved in translation through space and a rectilinear component is always involved in rotation. Investigation of the interplay between these two factors in eccentric oscillation will be discussed in the third part of this report.

C. Passive Rotary Oscillation with the Subject at Varying Distances from the Axis of Rotation

As is obvious from the analysis of the sensory data in rectilinear oscillation, the latter is probably never free from rotary factors except under experimental conditions. Similarly, since both horizontal canals cannot possibly be at the axis of rotation at the same time, while under non-experimental conditions both are commonly at considerable distances from the axis, it follows that in actual experience the sensory data in rotary oscillation are seldom or never entirely free from rectilinear factors.

In the effort to bring this every-day complication of rotary and rectilinear factors under experimental analysis, we devised a rotating boom-platform. It consisted essentially of a wooden channel-beam 340 cm. long, one end of which was supported by our rotating platform, the other end by a double wire cable leading through an eye at the top of the rotating platform's tripod-support, directly in the axis of rotation and anchored to the brick wall, thus taking the strain off the bearings of the chair and providing for the stability of the boom-platform system. Turnbuckles at the point of attachment between cables and boom provided for leveling the latter. By seating the subject along the

boom at different distances from the axis of rotation rectilinear and rotary factors in oscillation could be experimentally combined in various proportions.

The periods of oscillation remained the same in the four experimentally used distances of the subject's canals. The amplitudes, average velocity, and average acceleration varied, however, as the subject varied his position between the point of attachment of the driving mechanism where they are maximal and the axis of rotation of the boom-platform where they are minimal.

Four different periods and six different amplitudes were used to experimentally obtain four different average accelerations at one frequency, and four different frequencies at one average acceleration at each distance. The following table gives the amplitudes, frequencies, and average accelerations for each position from the center of rotation:

Amplitude cm.	Total Distance per Oscillation	Frequency Sec.	Average Accelerations for Positions			
			326 cm.	217 cm.	109 cm.	3 cm.
2	4	4	1.55	1.03	.52	.014
3.2	6.4	4	6.21	4.14	2.07	.057
8	16	4	99.2	66.1	33.1	.91
5.1	10.2	4	24.8	16.5	8.3	.228
6.6	13.2	6	24.8	16.5	8.3	.228
8	16	8	24.8	16.5	8.3	.228
10.6	21.2	12	24.8	16.5	8.3	.228

The first four combinations have the same frequency with varying average accelerations. The last four have the same average accelerations with varying frequencies for each position. It will be noted, however, that the average acceleration varies from position to position in each case.

These several values were not arbitrary, but were selected to fall within the range of sensitivity of both subjects for both the rectilinear and rotary components. On account of the differences in sensitivity, however, it was impossible to select a single series of distances which evoked an identical percentage of right responses for both subjects. Each position really has a different stimulus value for the two subjects. This would be unfortunate for an analysis of the sensitivity to the two factors, if that had not already been accomplished. The arrangement's main claim to consideration is the marked differences in the reactions of the two

subjects to the same combination of rotation and rectilinear translation consequent to their differences in relative sensitivity to the two factors. It is a conspicuous success as a device for demonstrating individual differences in the relative sensitivity of the two vestibular mechanisms. The order in which the experiments were conducted is 326, 217, 109, and 3 cm. from the axis respectively.

1. *Accelerations and Frequencies Evoking 50 Per Cent Right Responses*

Figure 27, *A,* shows the variation in accelerations evoking 50 per cent right responses, with the frequency constant at 4 seconds

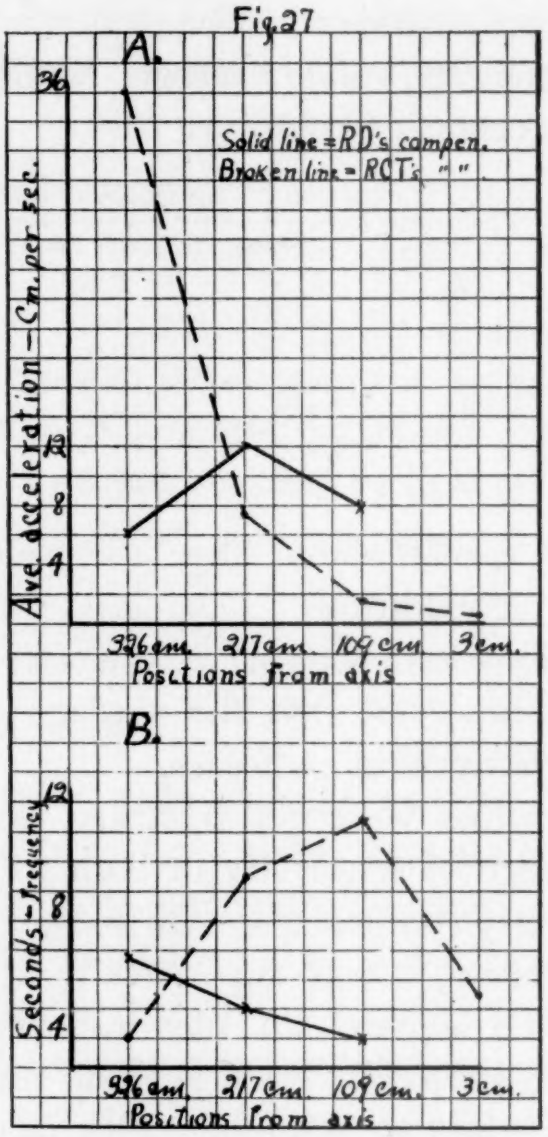

FIGURE 27. *A,* variation in vestibular sensitivity to average accelerations evoking 50 per cent right responses with the frequency constant at 4 seconds for the four distances from the axis.

B, variation in vestibular sensitivity to frequencies evoking 50 per cent right responses with varying accelerations as the axis is approached.

from position to position, for the rotary component in the case of RCT and the rectilinear component in the case of RD. *B* gives the frequency in evoking 50 per cent of right responses, with varying average accelerations from position to position, for both subjects. The rectilinear component in the case of RCT, and the rotary component in the case of RD were not regularly perceived, except in the first position (326 cm.) for RCT and the center position for RD. This seems to follow naturally from the fact that the rotary sensitivity of RD differed from that of RCT more than the rectilinear. Since the average sensitivity determined our experimental condition, the actual stimuli favored the rotary component for RCT and the rectilinear component for RD.

Figure 27 shows greater variation in the rotary sensitivity of RCT than in the rectilinear sensitivity of RD. As the average acceleration decreased, varying the distance from the 326 cm. position to the axis, the rotary sensitivity of RCT became lower. There is no consistent tendency in this respect for RD, but his frequency sensitivity rises as the average acceleration becomes less from position to position. The frequency sensitivity for RCT becomes lower in the second and third positions, notwithstanding a decreased average acceleration. The tremendous gain in the adequacy of RCT's perception of rotary motion as the axis of rotation is approached demands further consideration.

2. *Relations Between the Average Acceleration, Frequency and the Percentage of Right Responses at Various Distances from the Axis*

These relations are highly complicated and differ conspicuously for the two observers. There seems to be, however, a certain reasonableness in the variations when they are regarded in the light of the individual differences in threshold.

Figures 28 and 29 show the relation between the logarithms of the average accelerations and the percentage of right responses for RD and RCT in the four positions varying in distance from the axis of rotation, when the frequency remained constant at four seconds. To condense the upper end of the scale the ordinate

is shown in logarithms of the average accelerations. The abscissa represents the percentage of right responses.

In the case of RD the compensation to the rotary component was small in the 326, 217, and 109 cm. positions. In the center

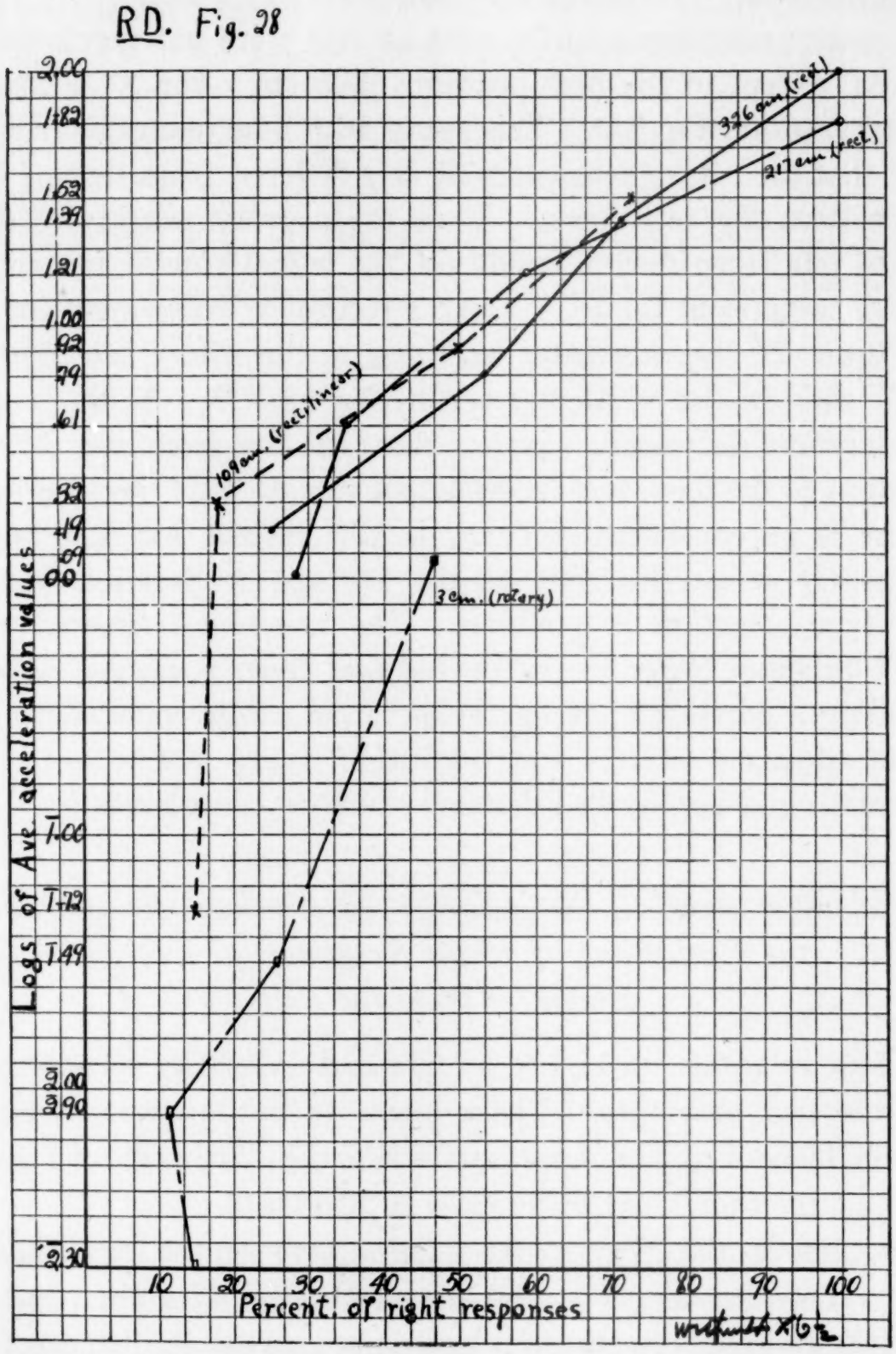

FIGURE 28. RD. Relation between the logarithms of the average accelerations and the percentage of right responses with the frequency constant at 4 seconds for the four distances from the axis. The three farther distances represent the rectilinear component.

position, however, even where the acceleration was greatly reduced, RD perceived rotary motion to a greater extent, the highest acceleration evoking slightly less than 50 per cent right responses. The curves of RD in Figure 28 show a rather close similarity with one another as far as the rectilinear component is concerned.

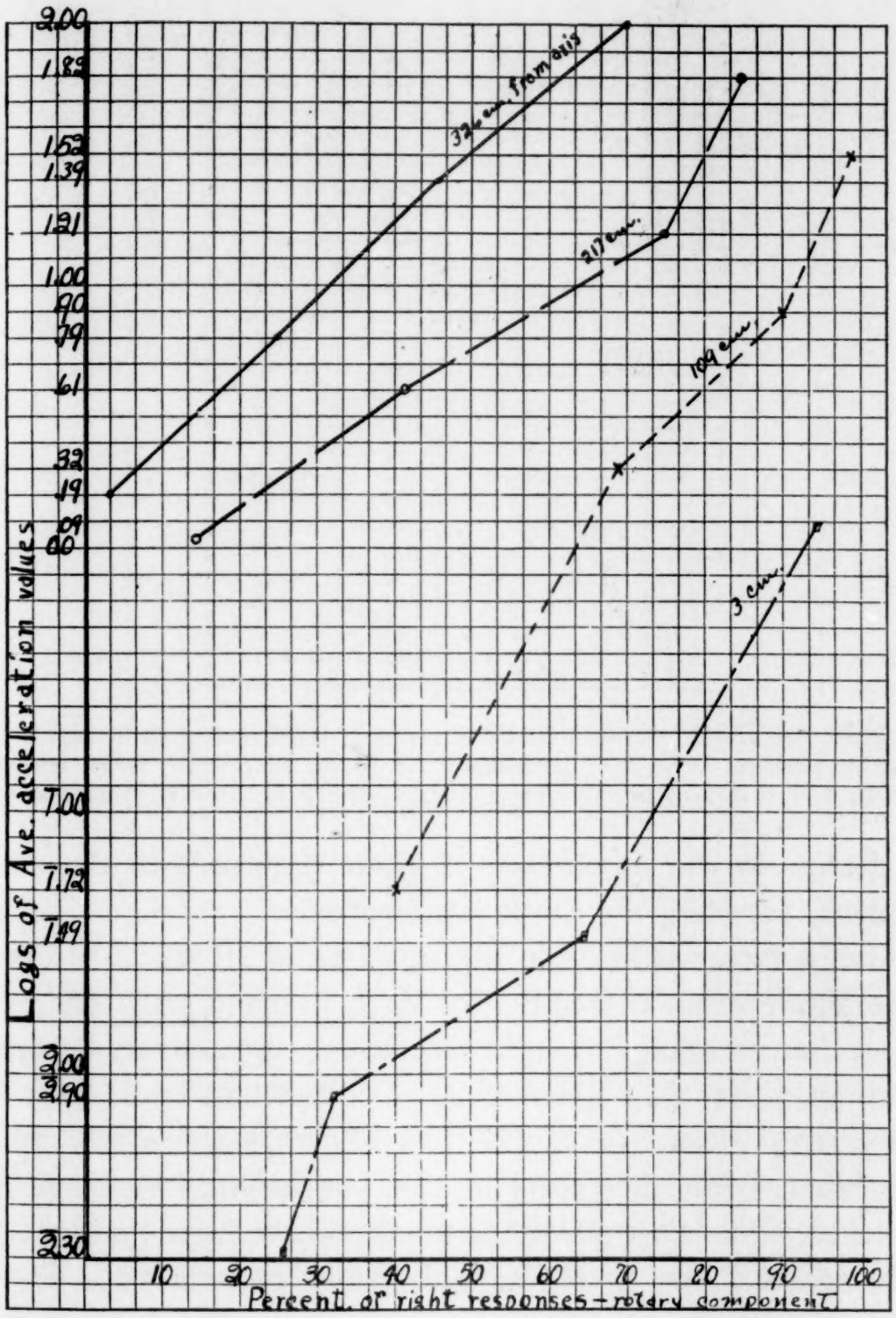

FIGURE 29. RCT. Same arrangement as in Figure 28, except all four curves represent the rotary component.

In case of RCT, Figure 29, the rectilinear component played a minor part in consciousness compared with the rotary component in all positions except the first (326 cm.). It will be noted further, that as the distances from the axis change there is a

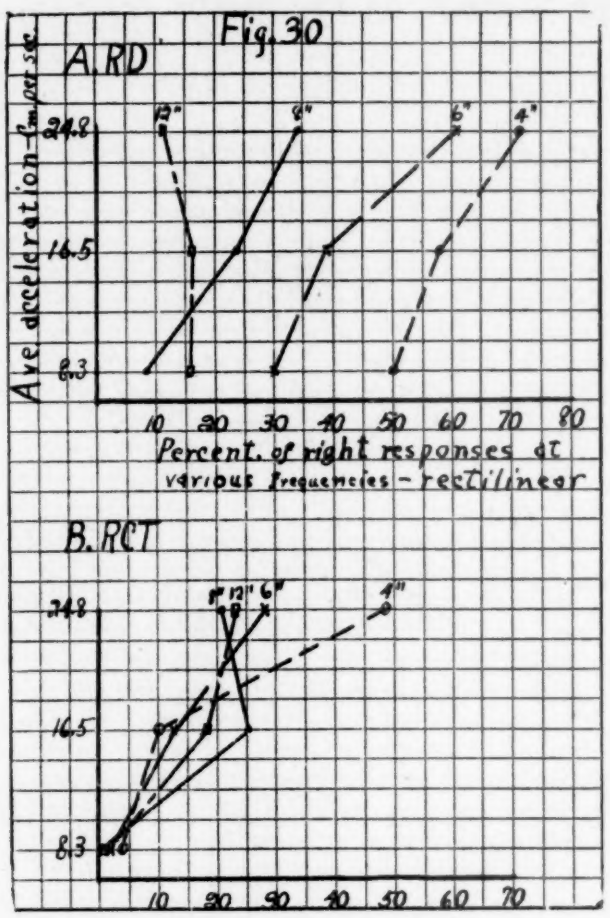

FIGURE 30. *A* and *B*, relation between average acceleration as it varied from position to position and the percentage of right responses with frequency constant at 4, 6, 8 and 12 seconds respectively for the rectilinear component.

great change in the percentage of right responses to the rotary component, favoring the lower accelerations.

The main facts disclosed in Figures 28 and 29 are: (1) As the average acceleration decreased for each position with frequency constant, the percentage of right responses progressively decreased for both subjects; (2) the rectilinear component curves for RD for the three positions (326, 217, and 109 cm.) are closely similar to each other, while the rotary motion becomes more conspicuous when the rectilinear component is maximally reduced; and, (3) in the case of RCT the curves have the same general slope for the rotary component, but show a marked increase in the perceptibility of this component as indicated by the percentage of right

responses as his position approached the center, notwithstanding a marked decrease in acceleration. This increase in perceptibility might hypothetically be due either to improvement by practice or to the gradual elimination of a competing rectilinear component. These hypotheses will be considered further in section 3.

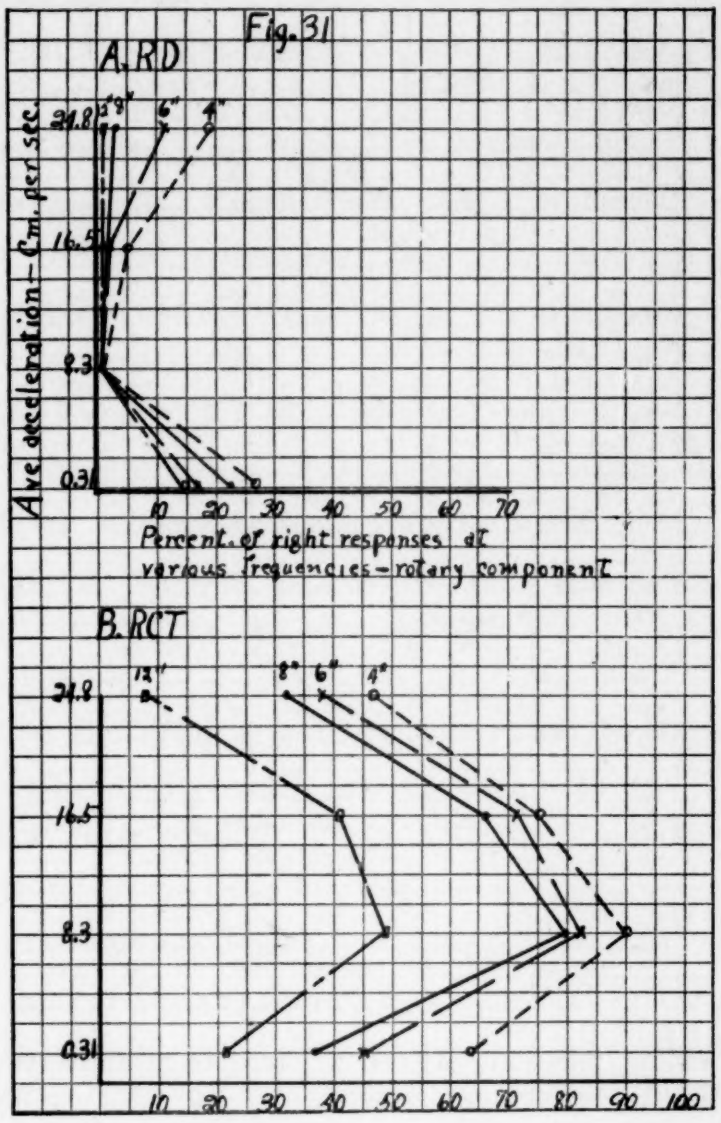

FIGURE 31. *A* and *B*, relation between average acceleration and percentage of right responses at frequencies of 4, 6, 8, and 12 seconds for the rotary component at four distances from the axis.

The average acceleration of the canals changes from position to position as the subject moves towards the axis decreasing by one-third at each position for any given frequency. As the average acceleration decreased, the percentage of right responses decreased for both RD and RCT, as shown in Figure 30. In the case of RD the more rapid frequencies, with one exception, produced a more adequate perception of oscillation in the rectilinear

component. There is more variation in this respect in the case of RCT. The relationship between the acceleration, frequency, and percentage of right responses is fairly consistent for each of the several positions and from position to position.

Analogous relationships for the rotary component for RD and RCT are shown in Figure 31, A and B. Here we find an entirely

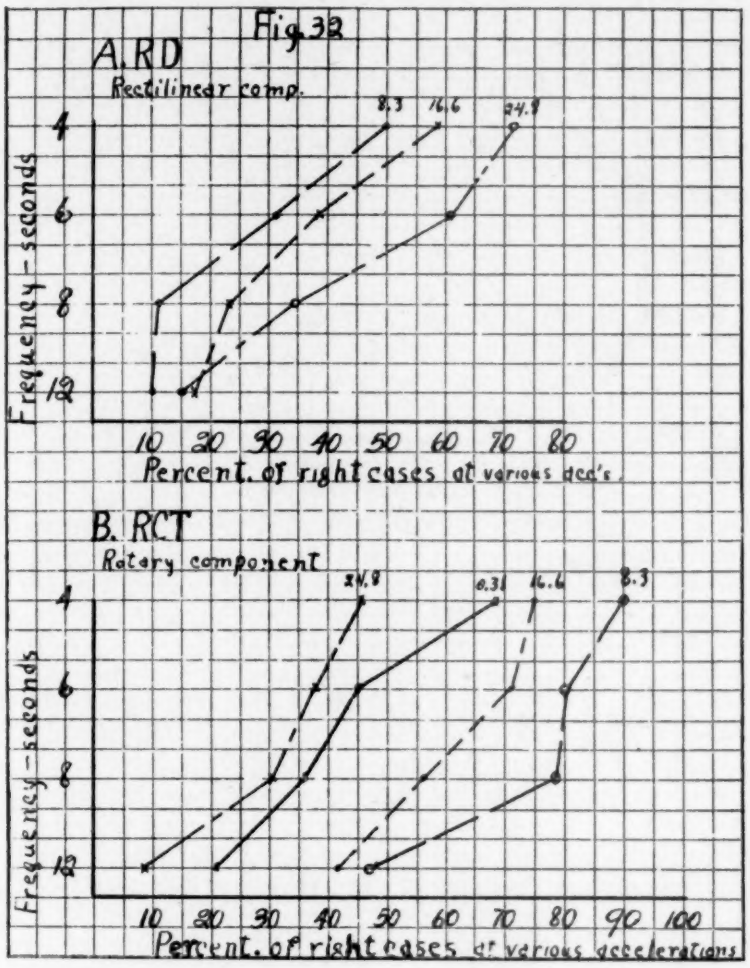

FIGURE 32. *A* and *B*, relation between the frequency and percentage of right responses at constant average accelerations for the predominant components for each subject.

different set of curves as compared with those of the rectilinear component. In the first place, there are four different positions in which rotary motion was perceived and only three in which rectilinear motion was perceived, because there is practically no rectilinear stimulus at the axis. Furthermore, as might have been predicted from his threshold measurements, perception of the rotary component by RD is relatively infrequent in all positions. The curves show a significant number of right responses in the higher accelerations at the 326 cm. position and on the axis, where

the rectilinear component is practically eliminated. In the case of RCT the rotary and rectilinear components are about equal in the 326 cm. position (compare acceleration 24.8 in Figures 30 and 31 B). In the next two positions, 217 cm. and 109 cm., the percentage of right responses in the rotary component becomes progressively greater, while the percentage of right responses for the rectilinear becomes progressively diminished. At the axis, however, in the case of RCT, the percentage of right responses for the rotary component, even though the rectilinear component was reduced to a minimum, diminished with the decrease in acceleration. It will be noted further that the percentage of right responses regularly decreases with a decrease in frequency at equal average accelerations.

A and B in Figure 32 give the relation for RD and RCT between the frequency and percentage of right responses for constant average accelerations for the predominant component for each subject. As the frequency becomes greater, the percentage of right responses becomes progressively greater for each average acceleration.

The influence of frequency as shown in Figure 32 appears somewhat greater than was shown in Figure 9, C and D, especially in the case of RCT. It will be noted that Figure 32 exhibits responses to a greater number of frequencies and accelerations than the earlier figure. This fact and the more orderly configuration of the curves make the results presumptively more reliable; but from our data we cannot be sure whether they are referable to a peculiarity of the receptor or to unperceived or undifferentiated accidental cues arising from slight imperfections in the smoothness of oscillation. The mechanics of the platform bearings and drive favor the former interpretation.

3. *Improvement of Compensation from Trial to Trial and from Position to Position for the Rotary and Rectilinear Components*

Figures 33 and 34 give the comparison between the percentages of right responses to the rotary and rectilinear components from day to day and from position to position. The broken lines repre-

sent the rectilinear component, the solid lines the rotary; each point on the curves represents a daily average. The total average for each position for ten days is represented by the short, heavy horizontal lines for the rotary component, and heavy, broken lines for the rectilinear.

In the case of RD, as the average acceleration decreased from position to position, the average percentage of right responses

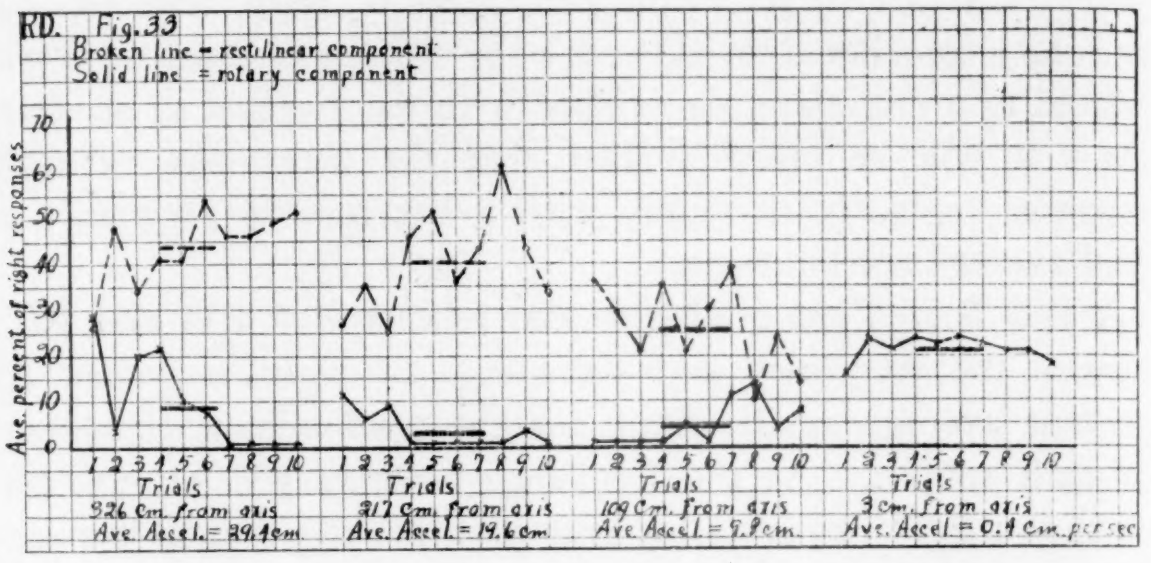

FIGURE 33. RD. Comparison of vestibular sensitivity to the rotary-rectilinear components from trial to trial and from position to position in terms of average percentage of right responses for all amplitude-frequency combinations.

decreased for the rectilinear component. For the rotary component it decreased from the first position to the second, but increased from the second to the third and fourth. It is clear in the case of RD that the rectilinear component was dominant in consciousness in all positions except the center. Quite regularly a high point in the rotary oscillation curve is coincident with a low point in the rectilinear, and *vice versa.* For RCT the rotary and rectilinear components are about equal in the first position; but from this position to the center a progressive divergence between the two components is evident. As the rectilinear component becomes less, due to a decrease in acceleration from position to position, the rotary component becomes progressively greater for two positions, notwithstanding a decrease in acceleration. This is in general congruent with data given in previous figures. Either improvement by practice has taken place, or the

rectilinear component produced an inhibitive effect upon the rotary component in the first positions, so that as the rectilinear component decreased the rotary motion was perceived more adequately.

This latter hypothesis would account for certain differences in the curves of the two subjects, since, due to relative differences in

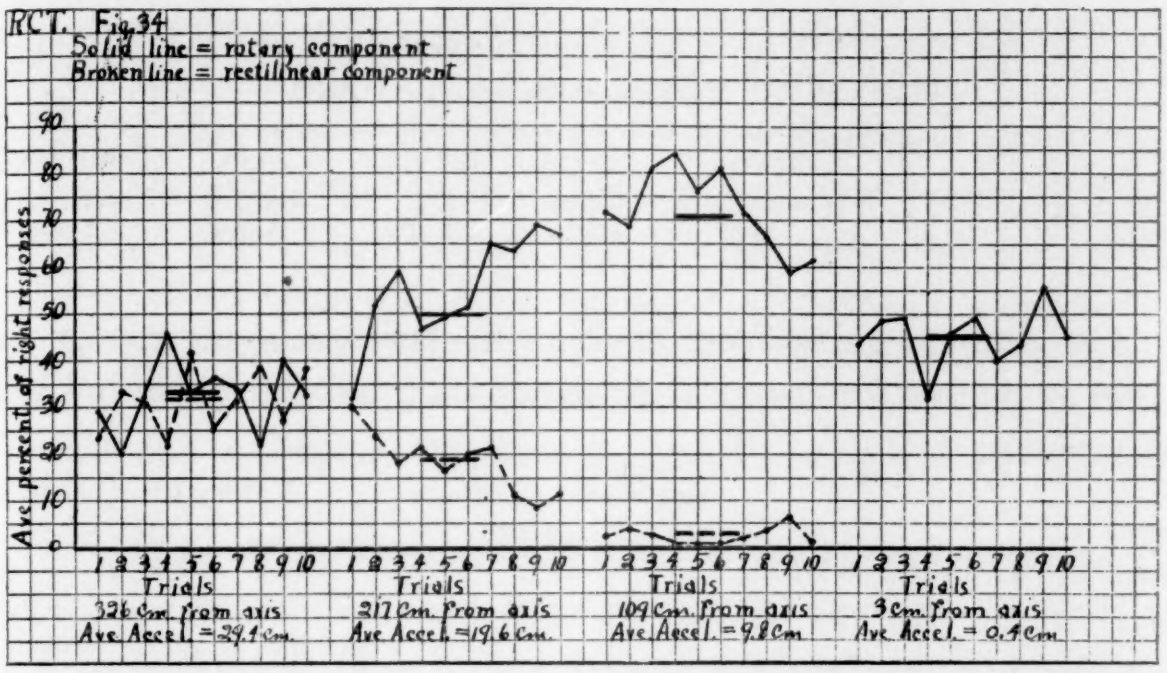

FIGURE 34. RCT. Same arrangement as in Figure 33.

sensitivity which we have already discussed, the rotary component was conspicuous for subject RD only at the axis, while the rectilinear component was most conspicuous for RCT at the position of greatest distance from the axis. This explanation would apparently bring our data under Heymans' (17) law of inhibition of a less intense by a more intense stimulus.

In order to determine how far this gain in the percentage of right responses to the rotary component for RCT was due to improvement by practice we subjected the data to further analysis of two sorts—namely, (1) we compared the average percentage of the first three trials with the average percentage of the last three trials for each position, and (2) we calculated the gain in percentage of right responses for identical accelerations in all four positions from the axis.

The total average percentage of gain of the last three trials over the first three trials is as follows:

	Rectilinear Component Various Positions from Axis			
	326 cm.	217 cm.	109 cm.	Total Ave.
RD	0.6%	12%	—5%	2.5%
RCT	10%	2%	—14%	—.7%

	Rotary Component Various Positions from Axis				
	326 cm.	217 cm.	109 cm.	3 cm.	Total Ave.
RD	—17%	—8%	8%	—1.5%	—4.6%
RCT	3%	19%	—9.4%	1.6%	3.5%

The average gains from position to position in percentage of right responses for identical accelerations in all four positions are as follows:

	Rectilinear Component	Rotary Component
RD	—2.4%	1.3%
RCT	—19%	29%

Comparing the average percentages of gain from trial to trial with those from position to position it seems clear that some other factor aside from improvement by practice operated to produce the gains from position to position. The facts, that the rotary stimulus is more effective for RCT and the rectilinear for RD corresponding to their respective thresholds, and that as one component decreases with a decrease in stimulus intensity the stronger component becomes more conspicuous to the almost complete exclusion of the weaker, increase the probability of separate, more or less rival receptor systems for rotary and rectilinear oscillation.

4. *Perception of Motion During Periods of No Physical Movement*

The following table gives the percentage of the total number of still-periods (20 for each position) and the percentage of the total time during the periods that motion was perceived:

Position	Percentage of Total Number		Percentage of Duration	
	RD	RCT	RD	RCT
3 cm.....	55	75	30	37
109 cm.....	57	75	29	45
217 cm.....	55	75	21	44
326 cm.....	40	75	28	34
	52	75	27	40

RD perceived motion during 50 per cent of the 80 still-periods and 27 per cent of the time during the still-periods; RCT perceived motion during 75 per cent of 80 still-periods and 40 per cent of the time. Out of the 12 still-periods that occurred at the beginning of the day's experiments RD perceived motion during 50 per cent of them and RCT during 90 per cent of them. The voluntary, compensatory responses during the still-periods at the beginning of the day's experiments showed a more definite rhythm and frequency than the responses during the still-periods interposed in the series.

Out of the 80 still-periods for all four positions RD perceived oscillatory motion with a definite rhythm 29 per cent of the total number and RCT 28 per cent of the total number. For RD the periods ranged from 4 to 20 seconds for each complete oscillation, most of them occurring within the range of 4 to 10 seconds. In the case of RCT the periods ranged from 4 to 20 seconds for each complete oscillation, with the most of them occurring within the range of 4 to 12 seconds. The results obtained from both subjects are closely similar in this respect and clearly indicate that some subjective factor operated in the perception of oscillation and modified the response to experimental stimuli.

V. INTERPRETATIONS AND THEORETICAL CONSIDERATIONS

Some of the implications of our data have already been discussed in connection with the several tables and figures. The intention of the present section is to bring together the more important previous interpretations and to make such additions as seem to arise from a consideration of the whole series of experiments.

A. *Thresholds*

In view of all the experimental data obtained with rotary and rectilinear oscillation, it is evident that the probability of right response is extremely variable for identical frequencies and intensities of stimulation. A frequency and intensity that may be perceived and responded to one moment may be unperceived the next. There appears to be no such thing as an oscillation threshold for either rotary or rectilinear oscillation in the sense of a fixed or invariant value of the stimulus at which perception emerges. This primitive meaning of the term is doubtless no longer current. In oriented circles, at least, threshold and the measurement of thresholds has long since come to have merely the value of a convenient central measure for the comparison of experimental events. As such we have found it useful in stating the comparative effectiveness of different modes of stimulation and the sensitivity of supposedly different receptors. As a statement of the orderly sequences and interrelationships of our data it would have been altogether inadequate. Only by comparing the percentage of correct responses to stimuli far below the supposititious threshold intensities could we have found the orderly relationships between acceleration and correct response, the mutual reinforcements and inhibitions of the various physical aspects of rotary and rectilinear oscillation, the summation of faint stimuli, the interplay of central factors, the inhibition of fainter by stronger components of the stimulus flux, the tendency

to rhythmic variation, and the inclusion in normal distribution of the negative effects of faint stimuli.

Our facts appear to mean that below the range of supposititious threshold values of frequency and intensity of stimulation the vestibular system is proportionately excited and response is elicited. Furthermore, it may be inferred that above a certain range of frequencies and intensities of stimulation of the vestibular system other sense fields are activated, such as the kinaesthetic and pressure senses. Thus a certain optimum range of intensities and frequencies of positive and negative acceleration is necessary to afford the most nearly adequate stimulus for the excitation of the vestibular systems.

B. *Variation*

Notwithstanding the irregularities of compensation for oscillation from stimulus to stimulus there exist certain rhythmical tendencies which indicate alternating periods of some sort of interference with and reënforcement of vestibular stimuli of constant frequency and intensity. The variation in the motor response from partial through zero to negative compensation, which may be characteristic of human behavior in general, may be explained for the most part by experimentally demonstrable interference and reënforcement of simultaneous stimuli, probably arising from various sources in the periphery and interacting with the main peripheral stimulation. But it cannot be attributed wholly to peripheral influences. There seems to be some evidence also for central reinforcing and inhibiting factors. This central factor seems to be proven by the responses during still-periods. Their origin is quite obscure and may prove to be very complex. Whether there is a definite rhythm or functional periodicity in continuous compensation for oscillation will be taken up in a subsequent paper, but the data we have render such a hypothesis reasonable.

Within our experimental data we have indications of summation by the repetition of stimuli. Moreover, since the physical properties of the stimulus are always the same for any given frequency-intensity combination of harmonic motion, the vari-

ation in the time of occurrence of reactions after the initiation of the stimulus indicates variation in the readiness of some part of the sensori-motor system to react. (See Table 5.) The reactions vary in the moment of occurrence all the way from the initiation to the cessation of the stimulus, though the majority occur on the first quarter of the oscillation. An analogous generalization is possible also for the incidence of reaction in a succession of harmonic stimuli.

The meaning of the large variation in the incidence of the reactions after the initiation of the first stimulus is not clear, even though considered as a summation process. Apparently, as the stimulation increases from intensities which are mostly unperceived, less summation is necessary for the elicitation of a response, and a shorter time must the stimulus continue to evoke a response. Conversely, as the stimulus is decreased from intensities which produce adequate responses to intensities which produce inadequate responses, the stimulus must endure longer to evoke a response.

In the case of summation of successive stimuli in vestibular excitation, as the frequency and intensity are decreased from values which produce adequate responses to values which commonly produce no response, the percentage of reactions requiring more than 1 or 2 stimuli for their excitation progressively increases. This means that when one half-oscillation stimulus alone is inadequate, if its effect is summed with the effects of one or more stimuli of like value, the result may be an adequate stimulus. And, when the effect of an inadequate stimulus of given length is summed with the effects of additional lengths of the same stimulus, the result may be an adequate stimulus.

C. *Negative Compensation and Perception of Motion During Still-Periods*

Negative compensation, or the perception of motion in the wrong direction, occurs quite consistently for both subjects at low frequencies and intensities of stimulation. Whether this phenomenon is to be attributed to the dynamics of the canals or vestibule, to the negative effects of faint stimuli, or to the inter-

action of various faint peripheral excitations is not a simple matter to decide.

Maxwell's work (18) suggests that during the acceleration period of the oscillation to the right the inert liquid in the vestibule and utricle excites the crista of the ampulla of the right horizontal canal. In turn, the deceleration period would have no effect on the right ampulla, but would cause the liquid in the vestibule and utricle to excite the crista of the ampulla of the left horizontal canal. The appropriate response, then, to the deceleration period would be what we have called the negative reaction. In view of the fact that negative reactions occur mostly during low intensities of stimulation, and seldom occur to adequate stimuli, tends to invalidate the hypothesis that the dynamics of the vestibule account for this phenomenon. Another point against the dynamics of the canals and vestibule in accounting for negative reactions is that the reflex movements of the eyes to oscillatory vestibular stimulation indicate that the acceleration and deceleration periods of each oscillation are responded to as a single stimulus, both periods producing reflex compensatory movements of the eyes in the same direction (19). However, this does not eliminate the possibility that the deceleration phase predominantly stimulated the antagonistic muscles. Further experimental evidence is necessary on this point.

Newhall and Dodge (20) have shown that faint visual stimuli which gradually become more intense by small increments have a negative effect which prevents perception until the stimulus reaches an intensity which would otherwise be clearly perceived. There is introspective evidence that faint stimuli arouse the vestibular system as a whole before defining the direction of movement. Just how far depression of one side of a balanced neural rivalry by the negative effect of faint stimuli may influence the domination of the competing side is a question of far-reaching theoretical and practical importance. Its investigation would demand special experimental techniques, but there are analogies in balanced muscular systems that create a certain presumption of probability. A common occurrence in our experiments in both rotary and rectilinear oscillation is that during a series of oscilla-

tions of inadequate intensity no perception of motion occurs, but in the following non-stimulation period, the subject compensates as though the platform were moving at a certain amplitude and speed. In view of the fact that in the non-stimulation periods, even at the beginning of the day's experiments, the subject responds as though the platform were oscillating, we have evidence for the hypothesis that complex central factors and peripheral factors may coöperate to produce a response and its conscious concomitants.

This central factor can hardly be classified as an after-image of oscillation, since the phenomenon occurs during the still-periods at the beginning of the day's experiments as well as after oscillation. For the same reason, it can hardly be purely a motor automatism. This is rendered still more improbable by the clear perception of motion that precedes or accompanies it. The hallucination of oscillatory motion is closely similar to, if not identical with, the perception of motion when the platform is in oscillation.

Some records show a sort of dying out of the response after a few seconds; some show a gradual increase in the response from zero to a regular rhythm; but these are not regular occurrences. The phenomenon varies from a "flash" of motion to several complete oscillations, which continued in some instances until the signal that the experiment was over.

Familiar examples of an analogous phenomenon may be observed in the after-effects of long continued oscillation. For hours or even days after a protracted ship voyage the individual may feel the pitch and roll of the ship. After continuous operation of a truck or tractor the jar and oscillations of the machinery may continue for several hours. Cases of unequivocal central excitation analogous to hallucinations of oscillation at the beginning of a session when after-images are ruled out are less obvious. We believe, however, that they show themselves in psychological set and similar predispositions.

Those cases where weak oscillation stimuli fail to elicit a perception of motion, while in the still-period immediately following the subject responds as though the platform were moving, may

indicate that some sort of interference between central and peripheral excitation processes took place during the oscillation period, and that on discontinuing the weak stimuli the central factor became dominant. Whether or not central factors entirely account for the negative reactions is a question on which we have no clear data. It seems quite possible, however, that the interaction between central and peripheral excitation processes may produce a negative response if the central factor is strong enough and in the wrong direction, or a positive response with faint stimuli if it happens to be in the right direction. In a system where some central or peripheral factor may produce hallucinations or illusions of oscillation it seems reasonable to suppose that similar factors may be operative throughout the experiment to modify the results of stimulation. In that case such variability as our data show would be the inevitable consequence of mutual summations and inhibitions.

It is possible that what we call central factors may be due to the misinterpretation of fortuitous kinaesthetic factors as in rectilinear oscillation. The spread of neural excitation into related neural systems is one of the best established facts of neural tradition. Dodge (21) found auditory verbal imagery easier to elicit when the auditory system was under excitement. It may be that either one of these conditions or both together may operate in different instances.

We conjecture that the phenomena which we have taken to be indicative of the interaction of the central and peripheral factors, would probably be more pronounced in abnormal subjects and might be diagnostically significant. In his experiments with psychoneurotics and schizophrenics Travis (22) found a differentiation between the two groups of abnormal subjects in their reactions to subthreshold and threshold visual and auditory stimuli, which indicated a predominance of the central factor in the case of the schizophrenics and a predominance of the peripheral factor in case of the psychoneurotics.

The implications of our data tend to extend to behavior the rôle of central factors that have been proven in perception, as, for example, in the psychology of reading. (23)

D. *Hypothesis of Separate Receptors for Rotary and Rectilinear Oscillation*

Rotary and rectilinear oscillation appear to be two quite different modes of stimulation; one is angular, the other rectilinear displacement. Positive and negative acceleration are essential characteristics of both. The receptor may be the same for both, but that seems improbable from our data. The only way we found to compare the relative sensitivity of the vestibular system for these two modes of stimulation is by the actual movements of the bony labyrinth in the two stimulation conditions. Such a comparison showed that the labyrinth averaged about 600 times more sensitive to angular acceleration, and 70 times more sensitive to angular velocity than to rectilinear acceleration and velocity. This seemed to indicate two separate receptors for rotary and rectilinear oscillation with different sensitivities. Furthermore, as the distance from the axis of rotation is increased, the rectilinear component becomes progressively stronger until the two components are about equal in eliciting voluntary manual responses; and if the distance is still increased, a point may be reached where the rectilinear component predominates over the rotary in arousing the vestibular system. This we regard as further evidence that there are two separate vestibular receptors for rotary and rectilinear oscillation. Otherwise, the oscillatory motion should always seem rotary because of the constant angular displacement regardless of the distance from the axis.

The alternative possibility that the same receptor may have different modes of irritability to rotary and rectilinear oscillation is not eliminated by our experimental data, but on the whole the separate receptor hypothesis seems more plausible.

E. *Interaction of Vestibular, Kinaesthetic, and Cutaneous Factors in Rectilinear Oscillation*

The distributions of the percentages of manual compensatory responses are approximately normal in all the different bodily positions in rectilinear oscillation. (See Figures 21 and 22.)

While the relationship between the percentage of manual compensation and acceleration is remarkably constant for the various bodily positions, the variability is much less in the sitting positions than in the standing positions. This indicates that the sensory data in the sitting positions are more homogeneous in character with less conflict among the various peripheral factors. In the standing positions, however, there are known to be at least three different kinds of more or less simultaneous sensory cues, the kinaesthetic, rotary-vestibular, and rectilinear-vestibular, sometimes one predominating sometimes another, but with a more regular predominance of the kinaesthetic cues when the body is free to move.

In the case of the two sitting positions, *viz.*, with the head-on-rest and with the head, chest, and abdomen strapped to the chair, the adequacy of compensation is closely similar in both; but the percentage of right responses is higher with the body strapped. In accordance with the Weber-Fechner law that slight changes in the intensity of pressure added to an already comparatively intense stimulation have little or no effect, the responses in the strapped-body position should have been less adequate than those of the head-on-rest position if pressure senses furnished the cues. This is not the case. Since the function of the pressure senses was reduced to a minimum in the strapped-body position, but was not curtailed in the head-on-rest position, while the percentage of right responses was not decreased in the former instance, it seems highly probable that at the low intensities of oscillatory stimulation under the circumstances of our experiments the pressure sense played no appreciable rôle. The case is somewhat complicated, however, in view of the introspective reports. In the body-strapped experiment the cues to motion seemed introspectively to be located quite consistently in the head, just back of the eyes; while in the head-on-rest position, in addition to the cues located in the head, pressure cues were noted on the back of the head, the shoulders, and hips. This indicates that without the body straps, sensory data were obtained from at least two sense fields, the pressure and the vestibular. This complication, as we have seen, did not aid perception. On the contrary it resulted in some

confusion, possibly due to the similar pressure effects of pulse and respiration.

The fact that the body-free positions in rectilinear oscillation present a lower threshold due to the kinaesthetic data, and that kinaesthesis is more nearly on a par with vision in interpreting the movements of our bodies is significant in an adequate account of vestibular sensori-motor behavior. Probably, in everyday experience we depend largely upon vision and kinaesthesis in making voluntary spatial adjustments, while the major function of the vestibular system seems to be in the reflex toxic adjustments of the skeletal and trunk muscles in maintaining bodily equilibrium, especially in body sway. The high correlation between body sway and overt manual compensation in rectilinear oscillation signifies that out of the two coincidently excited sensory fields the kinaesthetic data predominantly determine the voluntary response; while in the case where the kinaesthetic data are largely eliminated, and the vestibular alone remain, voluntary response is much less effective.

F. *Relative Rôles of Rotary and Rectilinear Components*

In view of the fact that both rectilinear and rotary components are present in rotary oscillation with the subject at a distance from the axis of rotation, the relative rôles of each component were experimentally ascertained at four different distances from the axis, with various frequencies and intensities of stimulation.

When the subject's position approached the axis of rotation, the rectilinear component gradually diminished and the rotary component became progressively dominant. This was especially true in the case of RCT. In the case of RD the change to the second position toward the center diminished both components. From here to the center the rectilinear component diminished and the rotary component became progressively clearer.

Probably both factors are really operative in determining consciousness, since introspectively the right side of the body usually seemed to the subject to move farther than the left side when the subject was oscillated in rotary fashion some distance from the

axis of rotation. And, as the axis was approached, the oscillatory motion of the platform seemed to increase the curvature of the arc through which the body passed. A small change in distance near the center produced a very noticeable change in the apparent curvature of this arc. This suggests the problem of determining the ability to discriminate distances from the axis of rotation by the feel of the curvature of the arc (body twist) of oscillation. If one horizontal canal were eliminated, the curvature of this arc would probably seem to be the same regardless of the distance from the axis.

VI. SUMMARY OF RESULTS

The following summary of the sensori-motor consequences of passive rotary and rectilinear motion applies directly only to sine-wave acceleration as stimuli and the relevant compensatory responses.

1. The concept of limen or threshold cannot be exclusively relied on to satisfactorily represent our data. We found no sharp line between positive compensation, no compensation, and negative compensation values. All occur in the distribution of our results, the first and last in varying degrees of adequacy. In the responses to stimuli intensities below the traditional limen we found a more or less orderly arrangement of phenomena, which was analogous to that occurring at stimuli intensities above the values necessary to evoke 50% right responses. The curves representing the percentage of right responses at varying intensities show a consistent and definite slope from the lowest to the highest intensities.

2. The average vestibular sensitivity to rotary oscillation for 2 subjects in terms of 50% right responses, with the subject at the axis, was 0.48 degrees per second in average velocity. The corresponding average acceleration value assuming that the canals are 3 cm. from the axis of rotation was 0.0276 cm. per second.

The analogous values for various positions in rectilinear oscillation in cm. per second are as follows:

	Average Velocity	Average Acceleration
Sitting, head- and body-strapped....	1.5	13 cm.
Sitting, head-on-rest.....	1.6	16 cm.
Sitting, body-free	.8	5 cm.
Standing, antero-posterior oscillation	1.0	6 cm.
Standing, lateral oscillation.....	.7	3 cm.

3. In sine-wave oscillation, both rotary and rectilinear, the percentage of right responses varies directly as the average velocity and average acceleration. The percentages of negative and zero responses vary inversely as the average velocity and average acceleration. An analogous relationship holds true for frequency

of stimulation and types of response in rectilinear oscillation. The results for frequency in rotary oscillation show less regularity.

4. Vestibular stimuli of constant intensity and frequency produce marked variability in the nature and adequacy of the voluntary manual compensations from stimulus to stimulus, from moment to moment, and from day to day. Our data indicate a varying constellation of peripheral and central factors and suggest certain rhythmical tendencies.

5. There is a marked variation in the point at which the response originates after the initiation of the stimulus. The responses occur all the way from the beginning to the cessation of each half-oscillation, with the majority occurring during the first quarter of the oscillation curve. Analogous variation was evident in the responses to both the first and successive half-oscillations in the several series.

6. As the frequency and intensity of stimulation decrease, summation of excitatory processes is more necessary to evoke a response. This is true for summation during the course of any given stimulus and for summation of successive oscillations.

7. A regular tendency was found to perceive motion in the wrong direction at low intensities and frequencies of oscillation. As the frequency decreased, the percentage of negative reactions occurring on the deceleration period of the oscillation increased. We know of no satisfactory explanation of this emphasis of the deceleration period at low intensities. Several more or less plausible explanations are discussed.

8. The experimental determination of the relative adequacy of the vestibular receptors and vision in the perception of oscillation with the subject at the axis of rotation showed that visual data permitted very much finer adjustment. Furthermore, more improvement by practice in the adequacy of compensation for oscillation was manifest with visual cues than without them.

9. Using the head as the mobile member for voluntary compensation to oscillation, we found that compensation under these conditions interrupts the perception of motion, thus confirming the traditional doctrine that the main receptors for rotary motion are localized in the head.

10. Whenever the body is free to move in a standing position, it remains perpendicular to the platform but a small percentage of the time, either during oscillation or when the platform is still. This swaying of the body during oscillation stimulated kinaesthetic receptors and caused them to participate very decidedly in the perception of motion. Furthermore, about 23 per cent of the body sway, with the axis at the feet or hips, produced an adequate stimulus for the semicircular canals. This complicates the sensory data in the perception of rectilinear motion by introducing a rotary factor.

11. There is a relatively high correlation ($.62 \pm .015$) between the extent of body sway which would otherwise be of sufficient amplitude to excite the semicircular canals and the amplitude of manual compensation curves. The manual response, under such circumstances, is regularly negative, indicative that the voluntary compensation is made to kinaesthetic data from a reflex bodily over-compensation. The rotary-rectilinear vestibular data are apparently inhibited. The low correlation ($.37 \pm .022$) between the body sway of not sufficient amplitude to arouse the canals and compensation indicates that under such circumstances the rectilinear vestibular factor predominantly determines the response. Apparently there is rivalry between the rectilinear-rotary vestibular data and the kinaesthetic in the standing positions.

12. Experimental isolation of the kinaesthetic factors in body sway proved that kinaesthesis is more than 10 times more adequate than the vestibule in perceiving oscillatory motion in rectilinear directions. This explains why the extent of motion seems to be the major characteristic of the stimulus in arousing the kinaesthetic receptors, while frequency has little or no effect.

13. The average sensitivity of the vestibular receptors for rotary oscillation is 70 times greater than for rectilinear in terms of the average velocity of the bony labyrinth in the two situations, and 600 times greater in terms of average acceleration. Such a difference of sensitivity in terms of the physical stimulus probably indicates two separate receptors for the perception of rotary and rectilinear oscillation respectively.

14. Rotary oscillation, with the subject at various distances

from the axis, proved to be an ideal arrangement for combining the rotary and rectilinear components in varying proportions, and also for exposing individual differences in this respect. The rectilinear component was predominant for one subject (RD) and the rotary for the other (RCT) in our particular stimulation conditions. As the axis of rotation was approached, the rectilinear component progressively decreased and the rotary progressively increased in affectiveness as a stimulus mode. The stronger component apparently inhibits the weaker. A distance from the axis was reached in the case of RCT where the two components were approximately equal. At this point the two components are apparently in rivalry and alternate in producing the response. This seems to be further evidence for the hypothesis of two separate receptors. In some instances the response appears to be a resultant of the two components.

15. It was shown that the gain from position to position in the percentage of right responses to the rotary component was not due to improvement by practice, but probably due to the elimination of an inhibitive effect of the rectilinear component.

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